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Evaluation of the relationships between measured archery bow performance and archer sensations

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A research thesis submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Doctor of Philosophy in Engineering.

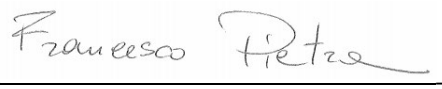
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Abstract

Archery is a precision sport in which the athlete is required to hit the centre of the target with accuracy and consistency. In archery, the interaction between the archer and the bow is of fundamental importance to guarantee performance. Unfortunately, there is no literature to support archers in selecting their bows. It is not always clear if new designs improve performance, due to the complex interaction between the archer and the bow, and it is not simple to measure if the archer-bow combination is better. In this thesis, a mixed research methodology is utilised to evaluate the relationships between the performance, the design and the athletes' sensations in using archery equipment. In the context of this thesis, the term *performance* refers to any measurable quantity related to the use of the bow (vibration and emitted sound on shooting, accuracy on target, behaviour of the bow on arrow release, etc.). The term *design* refers to the different ways of configuring the bow or the various options in choosing archery equipment. The proposed methodology is divided into four steps: selection of the design details to analyse; definition of a set of measurable quantities to evaluate change in performance due to change in design (objective metrics); definition of a set of metrics related to the archer experience with the various designs (subjective metrics); and analysis of the correlations between the defined metrics. The methodology was applied in three investigations, which were published as journal articles and are included in this thesis. The first paper explored the best distribution of stabilising weights for the barebow style, the second paper studied the effect of the introduction of damping on the shooting experience of the archers, and the third paper analysed the problem of the performance of different sets of archery limbs from objective and subjective points of view. This thesis describes how the methodological approach was tested and refined as it was applied to three investigations of increasing complexity. In each paper, the methodology demonstrated its capability of analysing complex problems that involve design, performance and athletes' sensations in using sports equipment. The study of the correlations between objective and subjective metrics led to a deep understanding of the analysed problem, suggesting less-than-obvious relationships between metrics.

An interesting finding from the first study is that the number of arrows required to achieve statistical significance in evaluating the performance of the bow depends on the skill level of the archer, as studied by JL Park. Notably, even for an Olympic-level archer, the commonly recommended 30 arrows are insufficient to evaluate the change in performance of the bow, in contrast with archery manuals. Additionally, the study highlights the importance of distinguishing between mechanical vibrations (low frequency) and the sound of the bow on shooting (high frequency) when assessing the vibrations of the bow. The main finding of the second study is that the introduction of damping into the bow effectively reduces the high-frequency components of the mechanical vibrations—specifically, the

sound during shooting—while exerting minimal influence on low-frequency vibrations. This reduction in high-frequency vibrations is perceptible to the archer, leading to an improved shooting experience. The primary findings of the third study reveal that archers can accurately judge the speed of the arrow with remarkable precision, but they are unable to reliably assess the smoothness of the bow limbs. Considering that the smoothness of the limbs is one of their key selling factors, finding that the archer is not capable of perceiving the smoothness is a finding worthy of future investigations.

The methodology utilised in this thesis may be applied to investigating other topics in archery and can be adapted to other sports where there is a necessity to understand how a change in the design of sports equipment can impact athletes' performance and athletes' perception of the sports equipment.

Acknowledgements

I would like to express my sincere gratitude to my fellow archers of the Archers of Zoo Lake Club (Johannesburg) for the time dedicated to this project and the enthusiasm for trying new archery equipment.

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Chapter 1

Introduction to the Problem and the Solution Methodology

1.1. Introduction

The problem of evaluating performance in sports and sports equipment is of great interest: on one side athletes are continuously trying to evaluate and improve their performance and, on the other side, sports brands are promising an increase in performance with the adoption of the latest technology[1]. It is often not clear if the new technologies are capable of improving performance, or if the promise of better performance is simply a marketing strategy to sell new sports equipment. Also, measuring the performance of the athlete/equipment combination in a sport like archery is not a simple task due to the difficulties in obtaining statistically valid data.

In addition to the problem of evaluating performance, there is the problem of how the change in design is perceived by the athletes. The relationship between perception/emotions and actual performance is complex. In some sports an increase in the performance of sports equipment corresponds directly with an increase in athletes' performance while, in other sports, this is not the case: the athletes might not be capable of using the new design to its best, or the feeling of the new design might be not right, reducing athletes' performance.

In this thesis, the study of the relationship between sports equipment performance and the athlete's perception of this performance will be studied. The problem will be analysed using a mixed research methodology [1] [2], evaluating initially the effect of a new design on the performance of sports equipment (quantitative study) and, subsequently, evaluating if these changes in performance are perceived by the athletes and how the athletes rate this new design (qualitative study). From the study of the relationships between sports equipment performance and athletes' perceptions, a better understanding of the impact of changes in sports equipment design is expected. The proposed mixed research methodology could be applied to various sports when there is a necessity to study the relationships between performance, design details and user sensations in sports equipment.

The sport selected for this investigation is archery. Archery is a precision sport in which the athlete is required to hit the centre of the target with accuracy and consistency, and the interaction between the archer and the bow is of fundamental importance to guarantee performance. Moreover, the modern bow is highly tunable equipment that can be adjusted for the particular needs of the archer.

[1] In the context of this thesis, the term *performance* refers to any measurable quantity related to the use of the bow (vibration and emitted sound on shooting, accuracy on target i.e. scores, behaviour of the bow on arrow release, etc.).

The tuning phase could be based on performance (the score obtained with a fixed number of arrows, although the number of arrows necessary to obtain statistically significant results is substantial), and on the sensations of the archer on shooting (on the adoption of a new bow configuration, the archers are normally requested to evaluate if they like the new configuration more or less, compared to the previous one). Since it cannot be quickly established that a change in equipment improves precision, the archer's perceptions become the most important criterion in the selection of equipment. Understanding the relationships between archery equipment design and archers' perceptions is therefore fundamental to the development of new designs focused on increasing precision and athletes' compatibility with the archery equipment. This promotes better sensations on shooting that can boost archers' confidence and may influence precision. Finally, the author of this work is an enthusiastic archer who has dedicated substantial time to studying archery from both the archery technique and the engineering perspectives, trying to develop a solid scientific foundation for the common practices typical of the sport of archery.

1.2. Performance in sport

In this thesis, a mixed research methodology is employed to address the problem of how to evaluate the relationships between performance, design details and user sensations in archery equipment. In the context of archery, sports equipment performance is defined as an engineering measurable quantity that can be used to compare designs. An example can be precision, but also the level of vibration of the bow or the noise of the bow on shooting. In the context of this work, the term *design* refers to the different ways of configuring the bow or various options in choosing archery equipment. In understanding problems that involve human experiences, the simple measurement of the performance of sports equipment is not sufficient to adequately understand how to improve the equipment design. Without considering the human aspect of the problem, the solution will be an interesting engineering exercise of limited value to the athletic community. In the sport of archery, a better design can only originate from the study of the interaction between archers and their bows, and from the study of what the archers perceive as a good design.

The use of a mixed research methodology to evaluate the performance of the bow is novel. The standard approach suggested in the archery manuals is the following: try something different on your bow (a new design feature), score thirty arrows with the new configuration and check if the score and the grouping are better than with the previous configuration [3]. This quantitative approach has been contested by Park as the score of thirty arrows is not statistically significant enough to decide upon the new configuration [4] [5]. The other common approach is the qualitative approach, a typical 'club' approach. The archer is requested to try the new configuration and if it 'feels good', then adopt it as it is better than the previous one (coach Dean McHendry, Archers of the Zoo Lake, Johannesburg). The

limitations of these two different approaches highlight the necessity of a novel approach to the problem of evaluating the performance of a new design to increase the athlete's performance while keeping in consideration the athlete's sensations in using the new design.

Comparative tests during equipment development are, probably, performed by equipment developers (Hoyt USA; Win&Win and Fivics South Korea; Gillo Italy; etc.), but the results are not available in the public domain. Moreover, the available papers on archery are few, mostly covering the physics of the bow on shooting (internal ballistic) and the arrow behaviour in flight (external ballistic). Marketing information from equipment developers is never technical enough to guide the archer in choosing new equipment. The use of a mixed research methodology developed in this work tries to fill the gap between the performance and club approaches by studying the relationships between archer's sensations and design details and between design details and performance. It is believed that this is a novel approach to the study of performance in the sport of archery. This thesis is the first attempt to use a mixed research methodology to gain in-depth insight into the sport of archery. While further research is needed to fully explore and refine this approach and its potential, the initial results are highly encouraging. They demonstrate the promising capabilities of this methodology and open the door to future studies focused on other aspects of the sport, potentially advancing both scientific understanding and practical applications in archery.

1.3. Research questions

The core of this PhD study is the use of a mixed research methodology to evaluate the relationship between performance (engineering measurements, quantitative studies), equipment design and athlete sensation in the sport of archery (qualitative studies). This methodological approach to the problem has to be flexible enough to apply to various archery equipment designs and, as a future development, to other sports.

The research questions are, consequently, the following:

- is it possible to define equipment performance measurements for the sport of archery and relate them to the design of the archery equipment?
- is it possible to measure the archers' sensations on shooting and relate them to the design of the archery equipment?
- and, finally, is a mixed research methodology capable of evaluating the relationship between equipment performance, archery equipment design and archers' sensations?

1.4. The mixed research methodology

As previously discussed, both the qualitative (QUAL) and the quantitative (QUAN) approaches to the study of performance in archery exhibit certain limitations. The historical approach to the problem

was a score-based method to assess improvements resulting from modifications to the bow configuration. This quantitative approach is outlined in various manuals [3] [6] [7] [8] and is normally accepted within the archery community as a standard practice. The approach suggests shooting thirty arrows, using the score as an indicator of performance differences between the tested configurations. The problem with this approach is the number of arrows necessary to achieve a score with sufficient statistical significance to differentiate between bow configurations. As demonstrated by Park in [4] and [5], even for an Olympic-level archer, evaluating performance changes due to modifications in the bow requires approximately 100 ends (600 arrows) to achieve sufficient statistical significance.

Nevertheless, the quantitative methodology can serve as a viable approach to studying archery performance, provided that an appropriate and carefully selected set of variables is used.

The qualitative approach is commonly used by clubs to evaluate different bow configurations. In this method, the archer shoots a limited number of arrows and provides subjective feedback on whether the new configuration “feels better” than the previous one. If the archer perceives an improvement, they are encouraged to adopt the new setup, based on the assumption that a more positive sensation with the bow will translate into better performance (coach Dean McHendry, Archers of the Zoo Lake, Johannesburg). This approach has been extensively tested in the field by the author (coach Francesco Pietra, Archers of the Zoo Lake, Johannesburg) and has proven quite effective, particularly with novice and beginner archers. However, its primary limitation is that archers unconsciously integrate various sensory inputs to form an overall impression of the shot, making it difficult to identify specific feelings or sensations. Before this study, it was unclear what specific feelings should be targeted—what exactly an archer perceives during arrow release—and whether there is a measurable correlation between these sensations and actual performance, or if archers can even perceive differences attributable to the design of the bow.

Considering the strengths and limitations of both qualitative and quantitative research methodologies, it was decided to study the problem with a mixed research methodology, aiming to harness the advantages of both and achieve a more comprehensive understanding of the problem. The mixed research methodology is based on a Pragmatic Worldview [2]: pragmatism is not committed to any one system of philosophy and reality. This idea applies to mixed methods research in that inquirers draw liberally from both quantitative and qualitative assumptions when they engage in their research. Individual researchers have the freedom of choice. In this way, researchers are free to choose the methods, techniques, and procedures of research that best meet their needs and purposes. Thus, in mixed methods research, investigators use both quantitative and qualitative data because they provide the best understanding of a research problem [2]. Mixed methods research involves collecting quantitative and qualitative data and combining or integrating the data to yield

insights or inferences from the combined data. Qualitative data typically involves open-ended responses that allow participants to share their perspectives in their own words, providing rich, detailed insights. In contrast, quantitative data usually comprises closed-ended responses, such as those found on questionnaires with predefined options, enabling numerical analysis and statistical testing. [1] [2]. In this work, various research designs were used to evaluate the best approach to the problem. In the first paper, an exploratory sequential mixed methods design was used, starting the research with a qualitative research phase exploring the views of participants. The data were then analysed, and the information was used to build a second, quantitative phase. In the second paper, an explanatory sequential mixed methods design was attempted. With this approach, the researcher first conducts quantitative research, analyses the results, and then builds on the results to explain them in more detail with qualitative research. It is considered explanatory because the initial quantitative data results are explained further with the qualitative data. In the third paper, a convergent mixed methods design was used. With this approach, the researcher converges or merges quantitative and qualitative data to provide a comprehensive analysis of the research problem. In this design, the researcher typically collects both forms of data at roughly the same time and then integrates the information in the interpretation of the overall results [1] [2]. A longitudinal approach [1] [2] was also considered, but eventually discarded as not pertinent to this work. Allowing the archer to get used to the new configuration of the bow is necessary for improving the archer's score [9] [10]. However, this acclimatisation process is not necessary when assessing sensations related to a new design. Based on the author's experience as both an archer and coach, just a few shots are sufficient to evaluate the characteristics and feel of a new design, aligning with the club's approach to assessing performance through subjective perception.

In this work, research methods are divided into quantitative and qualitative methods. For the quantitative methods, a particular design feature of the bow is considered for testing. Subsequently, an engineering approach is developed which considers the measurable effects of the different configurations to test the effect of that design feature on performance. Objective metrics (measurable quantities) are defined, and tests are performed to quantify the change in performance relative to the various configurations. For the qualitative methods, an archer-centred approach is developed to evaluate the impact of the tested configuration on the archers' shooting experience. The subjective metrics (archers' experience-related quantities) are defined to quantify the sensations of the archer using the tested configurations. The subjective metrics are collected by interviewing the archers and asking closed-ended questions. The answers are collected with the use of a questionnaire tailored to the specific study. The subjective metrics are then coded [11] [12] and compared to the objective metrics (the integration phase of the methodology [1] [2]), evaluating the Pearson correlation

coefficient r and the coefficient of determination $V = r^2$ between the defined metrics (Figure 1). The study of the correlation between objective and subjective metrics (metainferences [1] [2]) gives insight into the problem by seeking relationships between what is measured (objective metrics) and what is perceived (subjective metrics) by the archers.

The specific research methods will be presented in a dedicated methodology chapter for each paper.

The presented methodology was successful in collecting, analysing and interpreting the data, providing a deep understanding of the problem of the relationships between performance, design details and user sensations in archery equipment.

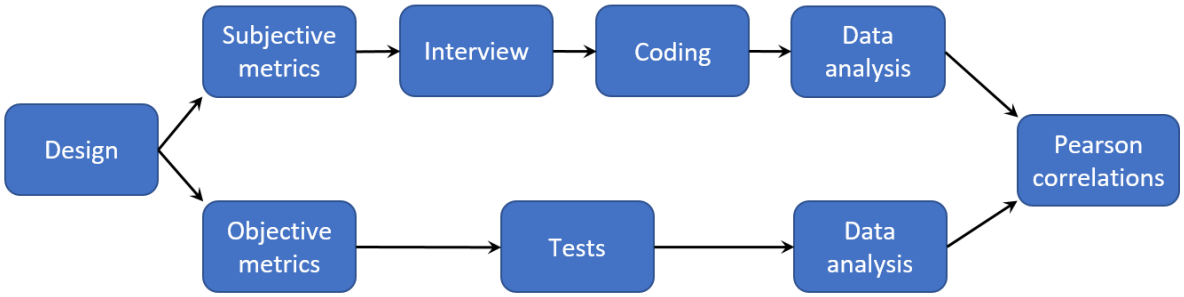


Figure 1 – Graphical representation of the mixed research methodology followed in this study.

1.5. Structure of the thesis

The thesis is divided into six chapters:

- Chapter 2 reports the general literature review relevant to this thesis. The scope of the chapter is to present the reader with the terminology typical of the sport of archery and to provide a basic understanding of the shape of the modern bow. The three papers reported in chapters 3 to 5 present a dedicated literature review focused on the specific arguments analysed in the paper.
- Chapter 3 reports on the first study that has been published in:
  Pietra F, Loveday P, Reid R. Analysis of preferred weight configuration for barebow shooting style. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. 2023; 0(0). doi:10.1177/17543371231155510.
  The paper is included in this chapter in the form of the "accepted manuscript," maintaining its original structure as submitted for publication. It is presented with single-line spacing to distinguish it from the rest of the thesis. The first page of the published version of the paper is available in Appendix A.
  The chapter also reports some background information on the development of the paper.

- Chapter 4 reports on the second study that has been published in:

  Pietra F, Loveday PW, Reid R. Objective and subjective measurements of the influence of dampers on the shooting experience of barebow archers. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. 2024; 0(0). doi:10.1177/17543371231213420.

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  The paper is included in this chapter in the form of the "accepted manuscript," maintaining its original structure as submitted for publication. It is presented with single-line spacing to distinguish it from the rest of the thesis. The first page of the published version of the paper is available in Appendix A.

  The chapter also reports some background information on the development of the paper.
- Chapter 6 discusses the evolution of the methodology as it was applied to three different studies and how these studies individually and jointly contribute to answering the research questions.

Chapter 2

Literature Review

This chapter is dedicated to introducing the reader to some concepts typical of archery, the terminology and the technique of shooting. Archery is part of our past and of our culture but, unfortunately, few people are practising this sport and films and television programs do not convey a historically accurate portrait of archery. For example, a typical battle archery scene is a line of archers holding the bow in full draw for several seconds and shooting volleys of arrows altogether at the command 'fire'. This way of shooting in a battle is typical of firearms but is historically inaccurate for bows: shooting a 140-160 pound English longbow requires a tremendous amount of strength and a very specific shooting technique, so holding the bow in full draw is virtually impossible for more than 1-2 seconds. In a more historically accurate archery battle scenario, the archers were organised in lines and, at the command 'release', were shooting as fast as possible, but everyone at their own pace [13].

2.1. Different types of historical bows and the evolution of the bow

From the Palaeolithic times until the advent of firearms in the 16th Century, the bow was not only a major hunting tool but also a primary weapon in combat. The bow proved to be vital to the many Central Asian nomads who conquered lands and founded dynasties in China, as well as to the attackers laying siege to the medieval castles in Europe. Found in virtually all cultures but for the Australian continent, bows display important and practical variations in construction, ranging from designs barely more than branches with a string attached to the extremities, to sophisticated mechanical devices made of different materials and with a complex design [14]. Fundamentally, a bow is a two-armed spring spanned and held under tension by a string. Drawing the bow places the back of the bow[2] (Figure 2) under tensile stress and the belly[3] (Figure 2) under compressive stress [14]. Drawing the arrow deforms the limbs that store potential energy. Releasing the bowstring transfers this potential energy to the string and arrow, converting the stored potential energy into kinetic energy of the arrow in flight. Historically, the development of the bow followed two different and coexisting paths with the design of the selfbow and the composite bow. The two development paths are shown in Figure 3, based on the short historical excursus on the bow presented in Appendix B.

[2] The back of the bow is the outside side of the limbs facing the target.
[3] The belly of the bow is the inside side of the limbs facing the archer.

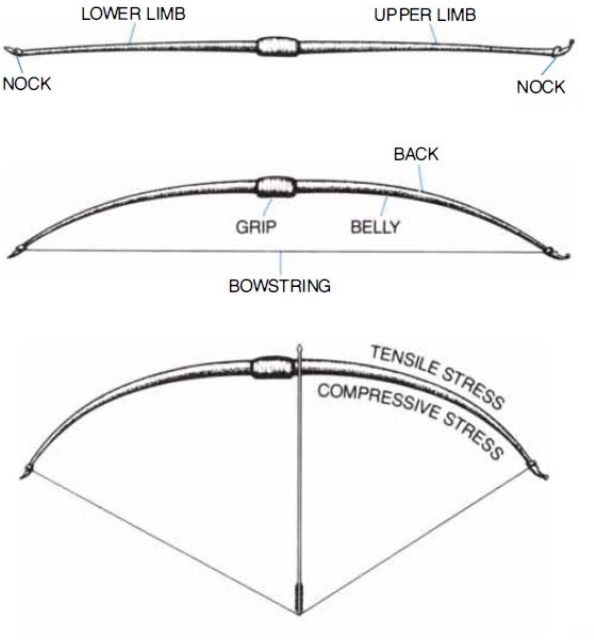


Figure 2 - The selfbow [14].

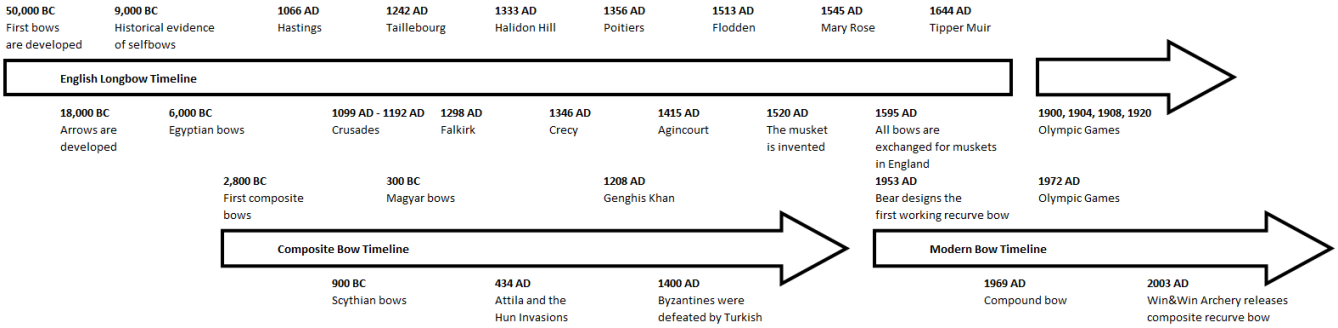


Figure 3 - English longbow timeline and Composite bow timeline [15].

The selfbow was made of one continuous piece of wood (stave), primarily yew or elm. By the Mesolithic period (circa 8,000 to 3,200 BC), the design of the selfbow was already established: a rigid grip area constricts wide, D-shaped limbs that gradually become narrower toward the tips. The early bow makers carefully scraped and thinned the belly of the limbs (a process called tillering), for the bows to display an even curve when strung and drawn. These characteristics contribute to a uniform distribution of stress along the length of the bow, thereby reducing the chance of breakage and improving performance [16] [17]. The designers of the Holmgaard bows also made them long, about 150 to 180 cm, roughly the size of the medieval longbow. A longer bow allows for an increased draw length, which contributes significantly to the speed of the arrow and the cast, the distance the bow will shoot an arrow [14]. A typical shape of the selfbow is shown in Figure 2, while Figure 4 shows historical selfbows [18].

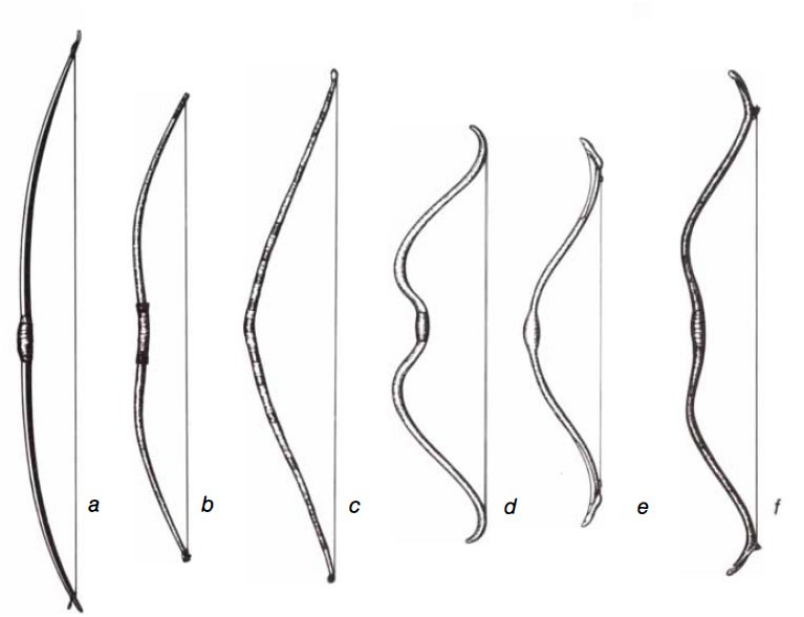


Figure 4 - The fundamental types of selfbows: (a) the medieval yew longbow, (b) the Teton Lakota sinew-reinforced bow, (c) the western Asian angular bow (Egyptian bow), (d) the Scythian bow, (e) the 17th Century Turkish bow and (f) the 17th century Crimean Tatar bow [14].

Although the selfbow design gave birth in Europe to the famous English longbow, this design has some limitations. It requires a long stave of seasoned wood (yew was the preferred choice for the wood), and the dimensions are not compatible with using the bow on a horse or in the situation of hunting in an area with dense vegetation. A typical evolution of the selfbow in the case of lacking good yew staves is the sinew-reinforced bow, where the sinew compensates for the poor performance of the wood (Figure 5) [19]. Another typical evolution of the selfbow is the reduction of the size of the bow for better handling in dense vegetation conditions, and the introduction of poison at the point of the arrow. This solution is typical of the African continent and, in particular, of the Pygmy population [20] [21].



Figure 5 - The Polar bow of Gap Museum. A long plait of interwoven sinew runs all along the bow for increased performance [19].

To reduce the size of the selfbow, in the 2nd millennium BC, the Asian bow designers concentrated not just on the architecture of the limbs but on the bow materials. In particular, Asian bowyers used adhesives derived from hide and fish swim bladders to glue animal sinew to the backs of their bows and horn strips, usually from the water buffalo, glued to the belly. The combination of sinew, wood and horn created the "composite" bow, a short-limbed bow used on horseback by the population between northern Asia to China and Turkey [14] [18]. The typical shape of a composite bow is shown in Figures 6 and 7.

Composite bows have been known and appreciated in Europe since the Crusades, where the Norman knights fought against Turkish mounted archers [22], and the distinctive recurved shape of the composite bow appears in medieval European tapestries [13] [23]. The reason the longbow was the weapon of choice in Europe was the necessity of the European army to mass produce the bows: the production time in medieval times for a longbow was about three days per bow, while the production time in the same period for a composite bow was three months per bow [22] [13]. However, in the late Middle Ages, the technology of the composite bow was adopted by crossbow makers to construct crossbow limbs more powerful than those of wood, before they were in turn superseded by limbs made out of steel [23].

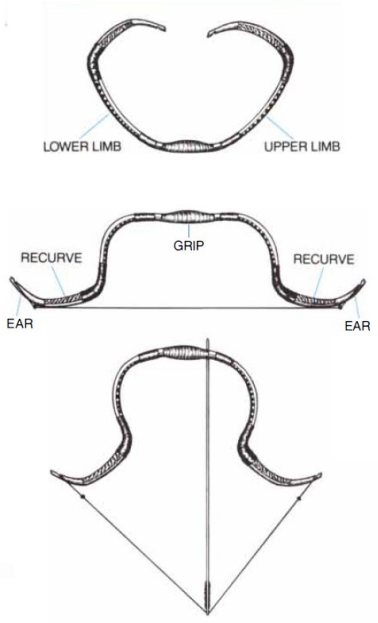


Figure 6 - Composite bow: (top picture) unbraced, (middle picture) braced and (bottom picture) fully drawn [14].

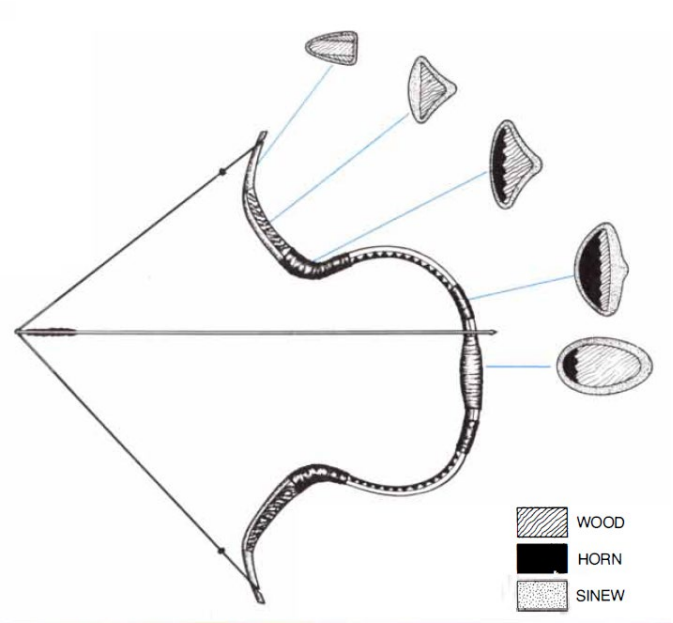


Figure 7 - Composite bow: internal structure at different positions along the bow [14].

2.2. Drawing techniques

Through the ages, archers have developed a number of methods for drawing the bow. Edward S. Morse (1885 – 1922), who pioneered ethnological research on this subject, defined five basic ways to

draw the bow: Primary, Secondary, Tertiary, Mediterranean and Mongolian [24] (Figure 8). Of all these drawing techniques, only the Mediterranean and the Mongolian remain in use today.

In the Mediterranean draw the thumb normally plays no part. Instead, the tips of the index and middle – or index, middle and ring fingers pull the bowstring (Figure 8, G-H). The index and middle fingers bracket the arrow and hold it lightly against the bowstring. This was the typical drawing technique used by the English longbow archers, and it is the standard drawing technique for Olympic archers. The draw has several variants, for example, modern barebow archers shoot with a three-finger-under-the-arrow technique, where just the index finger is in contact with the arrow.

The Mongolian draw is typical of the composite bow and archers of the East, both in the past and present. The arrow is held in the web between the thumb and index finger. To release the arrow, the locking finger is slipped off the thumb. With but few exceptions, the middle, ring and small fingers are not used and are normally curled out of the way (Figure 8, I-J). A protective device, usually in the form of a ring, is often worn on the thumb to shield it from the concentrated pressure of the bowstring as well as to allow for a smoother release [24]. Although the Mongolian draw is considered by many to be superior to the Mediterranean draw [24], but it is prohibited by the World Archery Federation rules for recurve and barebow archers [25].

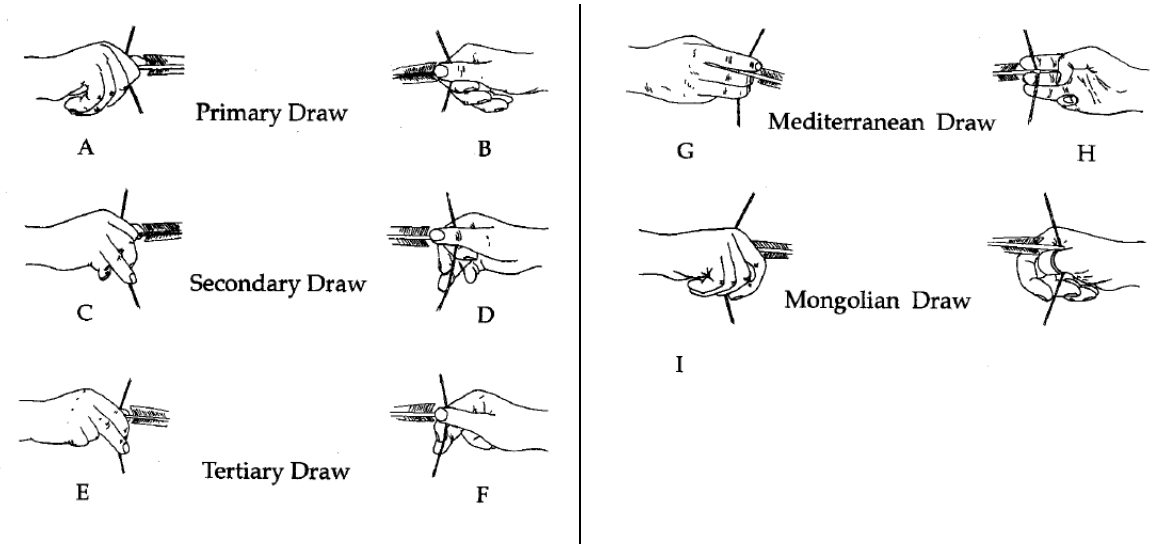


Figure 8 - Morse's five draws styles [24].

2.3. Modern archery

Modern Western archery can be dated back to the 1780s when the English longbow enjoyed a renaissance among the English aristocracy. Historical archery became a fashionable recreation for both men and women and a cultural way to connect with English traditions. Later, during 1819–1845, longbow archery developed into a mass movement, as it spread initially into the English middle class [26] [27], and then into the United States of America (USA). The first scientific study about archery is

dated 1937 by C. N. Hickman [28] and, successively, by P. E. Klopsteg in 1943 [29] who demonstrated that the longbow D-shaped limb cross-section is not the best from the stress distribution point of view, starting the process that created the modern bow. Klopsteg was also the first to solve the Archer's Paradox using speed-flash photography to describe the oscillatory behaviour of the arrow upon shooting. In 1969, the first scientific description of the working recurve bow by Schuster [30] was published. The name *working recurve bow* refers to the classification of the modern Olympic recurve bow: the limbs are initially curved toward the archer and then curved again away from the archer (*Re-curve*, Figure 9) and the tip of the limbs is flexible (*working*) in contrast with the rigid tips of the composite bows. The modern Olympic recurve bow design is a hybrid between the English longbow and the traditional composite bow (Turkish bow): while the tips of the limbs resemble the traditional composite bow being initially bent in the opposite direction of the draw, the recurve bow is longer than the traditional composite bow and similar in size to the English longbow [31]. In modern times, the dynamic behaviour of the bow was studied by Marlow [32], and Kooi [33] [34] [35] [36] [37]. Kooi also studied the internal ballistic, which is the behaviour of the released arrow when still in contact with the string [38] [39] [40]. Zaniewski studied the dynamic behaviour of the entire bow, including in the analysis also the stabilisation system (V-Bar, Figure 9) [41] [42] [43] [44] [45] [46]. All these studies contributed to the development of the modern Olympic recurve bow and to transforming archery into a recreational activity and a competitive sport. While the scope of the bow has changed over the centuries, the principles of precision, focus, control and repetition remain the same. As a sport, archery is accessible to a wide range of people, no matter their age, gender or ability. It is a widespread pastime in both developed and developing countries. Archery is also one of the few sports that can be practised by able-bodied and impaired athletes on a level playing field. Archery featured at the Olympic Games in the early 1900s and joined the programme permanently in 1972 [47].

The World Archery Federation (WA, also formerly known as FITA from the French Fédération Internationale de Tir à l'Arc) is the governing body of the sport of archery. WA is based in Lausanne, Switzerland and has five continental member associations and more than 160 national member associations that regulate, promote and develop the sport in their respective regions. WA is responsible for the Olympic and Paralympic sport of archery, and for organising international events, including a world championship in archery [47]. WA recognises three main categories of bow: the recurve bow, which is the style of bow used at the Olympic Games; the compound bow, and the barebow [25]. The barebow (Figure 10) and the recurve bow (Figure 9) use the same type of bow divided into a rigid centre called the *riser*, two flexible parts called *limbs* and a *string* to connect the ends of the limbs. The riser is made of aluminium alloy or composite materials; the limbs are made of a combination of wood, glass and carbon fibres; the string is made of High-Density Polyethylene

(HDPE), commercially known as Fastflight or Dynema. In the recurve style, the archer is allowed to use a stabilisation system, a sight and a clicker[4]. In the barebow style, sight and clicker are not allowed, and the stabilisation system is limited to weights attached to the riser [25].

The latest developments in recurve archery technology are based on the use of new materials: graphene for the limbs and Aluminium 6081-T6 for the riser. New manufacturing technologies are experimented with to create the riser: for example, additive manufacturing [48] and fused deposition [49]. The shape of the riser is continuously refined using topological optimisation [50] [51] [52].

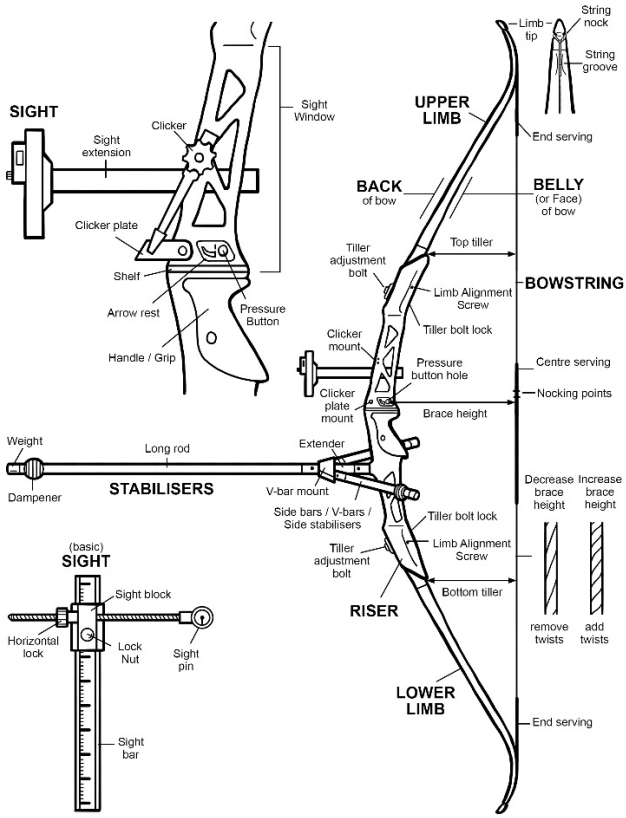


Figure 9 - Bow structure in the Recurve style [53].

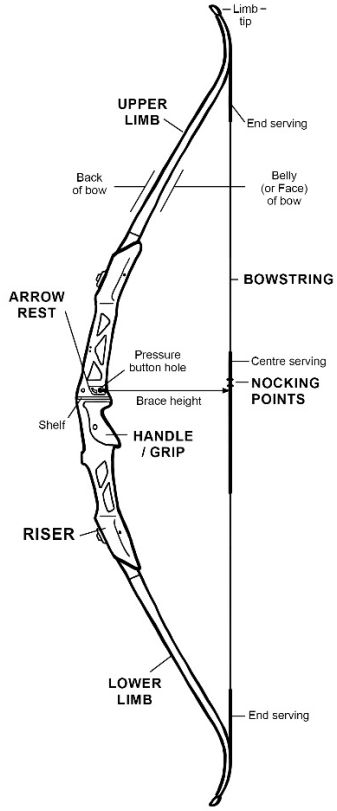


Figure 10 - Bow structure in the Barebow style [53].

The third type of bow, the compound, uses a levering system, usually of cables and pulleys, to bend the limbs (Figure 11). The pulley/cam system grants the user a mechanical advantage, and so the limbs of a compound bow are much stiffer than those of a recurve bow or longbow. This rigidity makes the compound bow more energy-efficient than traditional bows, as less energy is dissipated in limb

[4] The clicker is a mechanical device that helps the archers to keep their draw length consistent. The clicker is positioned over the arrow and, at the maximum draw, it impacts the riser with an audible 'click' sound. This sound is used by the archer as a trigger to release the string and shoot the arrow [107].

movement. The higher rigidity and the more advanced construction also improve the accuracy of the bow. Compound archers can use a mechanical release mechanism (trigger) to shoot the arrow [54].

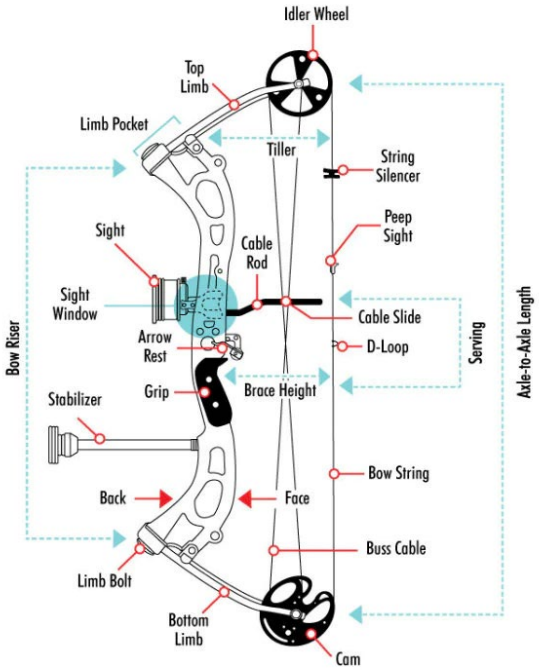


Figure 11 - Bow structure in the Compound style [55].

2.4. Aiming techniques in modern archery

Aiming techniques in modern archery depend on the type of bow, as defined by WA. Recurve and compound categories allow the use of a sight, whereas barebow archers rely on the tip of the arrow to aim at the target [25]. The typical sight utilised for a recurve bow is shown in Figure 12, while the typical sight for a compound bow is shown in Figure 13.



Figure 12 - Shibuya sight Ultima RC Pro 520-9-A Single Mount [56]



Figure 13 - Shibuya compound sight Ultima CP Pro 400-9A [57]

The primary difference between the two sights is that the compound sight can use multiple pins and magnification lenses, whereas the recurve sight has just one pin and no magnification lenses [25].

Barebow archers are not permitted to have a sight on their bow and therefore use two different aiming techniques: gap shooting and string walking. In the gap shooting aiming style, the tip of the arrow at full draw serves as a reference point, positioned at a specific distance below or above the centre of the target to account for the shooting distance [58]. In the string walking aiming technique, the archer positions the tip of the arrow on the centre of the target and adjusts for the shooting distance by moving the finger along the string. The hooking fingers 'walk' up and down the string to alter the angle at which the arrow is launched. The distance between the arrow nock and the hook is referred to as 'the crawl' [59].

2.5. The shooting sequence

The shooting sequence is the process an archer goes through during their shot. The following shooting sequence is typical of the Olympic recurve archers. It can be divided into the following four steps [60] (Figure 14):

Set-up	Divided into: • Stance (Step 1) • Nocking the Arrow (Step 2) • Set the Bow Hand (Step 3) • Set the Fingers on the String (Step 4)	In this phase, the archer reaches a stable body stance, nocks the arrow on the string and sets both hands on the bow in the correct position (grip and hook).
Predraw	Divided into: • Set-up and Predraw (Step 5)	In this phase, the archer aligns the shoulders in the correct position.
Anchor	Divided into: • Drawing the Arrow (Step 6) • Anchor (Step 7) • Target Alignment (Aiming) (Step 8)	In this phase, the archer draws the string to the anchor position and starts aiming at the target.
Follow Through	Divided into: • Expansion • Release (Step 9) • Follow Through (Step 10)	In this phase, the archer increases the draw from the anchor position until the clicker 'clicks' (expansion). Then the archer releases the string and ends the shooting sequence with the follow-through.

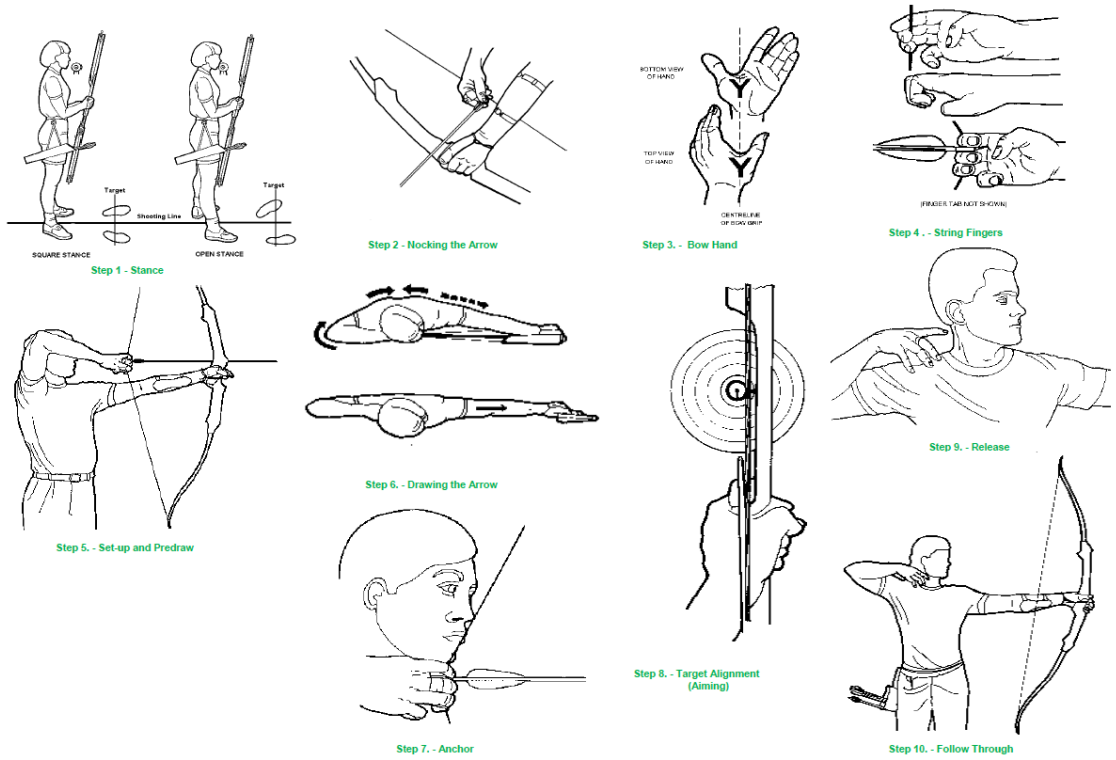


Figure 14 - The Shooting Sequence [61].

2.6. The study of performance in the sport of archery

Searching the available scientific publications on archery, no studies are available to relate design features of the bow to performance (the bibliometric analysis is presented in Appendix C). Comparative tests on various design solutions are also not available, and the only performance normally considered in the sport of archery is the score on target (the bibliometric analysis is presented in Appendix C).

One scientific study relates the archer's loss of score to the errors in the archer's shooting technique [62][5], and another examines the effect on the score of the choice of the diameter of the arrow in indoor competitions [63]. A third paper analyses the effect on the score of the choice of the vanes[6], vane position on the arrow, and string materials [64]. Expanding the research to the archery manuals, the definition of performance is again purely based on the score on target. Moreover, archery manuals never suggest a bow configuration or discuss the effect of a design feature on performance. All manuals are oriented to developing the shooting technique and then dedicate ample space to the tuning process [7] [9] [10] [65] [66] [67]. The tuning of the bow is the process that tunes the bow to

[5] The expression 'loss of score' is used by Lao, Chung and Park to indicate the points loss from the archer in a competition due to the lateral inclination of the bow on shooting (canting).

[6] Archery vanes, also known as fletching, are flight control surfaces that help stabilize, steer, and spin the arrows. They also help damping the arrow's oscillation and control its yaw (side to side movement), and pitch (up and down movement) [108].

the archer's shooting style, allowing the best performance [3]. The best performance is evaluated by considering both the maximum score and the dimension of the group of arrows on the target, for a limited number of arrows (from 12 to 30). As already reported, this approach has been contested by Park as the score of 30 arrows is not statistically significant enough to decide upon the new configuration [4] [5]. All these reference materials do not consider the archer's sensations on shooting as part of the tuning process, with the only exception being the brace height tuning, where the archer is required to minimise the sound of the bow on release to obtain maximum efficiency in the bow. None of these reference materials considers the effect of the design features of the bow on performance.

To overcome the shortcomings of the standard approach to performance, new studies are suggesting the evaluation of the archer's performance through biomechanical assessments of the movements of the archer's body on shooting. These studies concerning the biomechanical evaluation of the archery discipline reveal the need to create a standard and objective assessment of the quality of the archer's shooting technique based more on the execution of the shooting movement than on the points scored [68] [69].

2.7. The study of performance in other sports

When studying other sports like tennis, a similar situation arises. Ergonomics, sports engineering and biomechanics are all fields that have contributed to the understanding of the player/racket system and how to improve performance from a laboratory point of view. Confirming these improvements with evidence has been difficult given the system's complexity. To rectify these validation issues, racket developers have started supplementing traditional design and testing techniques with on-court measurements of ball and racket movements to gain a greater understanding of the interaction of these two systems. Unfortunately, there are virtually no studies that have compared common racket equipment with new designs to validate theoretical or experimental research in the laboratory. Comparative testing is presumably done by tennis equipment developers, although the results are unlikely to make their way into the public domain [70] [71] [72].

The sport of golf has the same problems in defining and evaluating performance as tennis. Interestingly enough, while searching for additional publications to compile this literary review, the author came across the papers from Roberts et al. [73] [74], which describe a very similar approach to the problem as developed in this work. Roberts et al. split the problem into two different studies, analysing the correlation between the vibration of the golf club and the golfer's sensation first, and the sound of the golf club and the golfer's sensation in the second paper. Although the approach to

the problem is similar, Roberts et al. did not apply a coherent methodology, and their studies were limited to simple comparisons between vibrations and sensation and sound and sensations.

Increasing the scope of the research on performance in sports, the relationship between emotions and performance in sports has been studied by sports psychologists. Few studies approach the complex relationship between discrete emotions and specific performance, and the majority of studies are in the area of the relationships between stress and anxiety and sports performance [75] [76] [77]. Other studies try to combine athletes' experiences during performance and the biomechanical characteristics of their movements to investigate sports performance [78] [79] [80]. In these fields of research, the athletes' performances are related to the biomechanical indicators describing the athletic technique and the athletes' experience in performing the athletic technique. The effect of design features on the performance is not considered. The necessity of measuring performance using common methodologies and specialised tools from statistical analysis [81] [82] is another field of research.

Tennis and golf are just examples of a great many possible sports that could be analysed for the evaluation of performance. More examples are beyond the scope of this work, but it is suggested to the interested researchers to think about how to adapt the presented methodology to their sport of interest. The proposed mixed research methodology is not exclusive to the sport of archery and could be adapted to other sports where the interaction between the athlete and the sports equipment could make a difference in performance.

Chapter 3

Selection of Weight Configuration Using Objective and Subjective Measures

3.1. Introduction

The first study in this work considered the best weight distribution in the barebow style. Barebow is one of the three recognised archery styles, along with recurve and compound (refer to chapter 2.3), with significant limitations in the type of stabilisation system that can be applied to the bow. In the barebow archery shooting style, archers are allowed to attach different combinations of weights to the riser to improve their performance [25]. Since there is no supporting literature to guide the archers, the process of optimising the weight distribution is by trial and error. Consequently, the research question was defined as the following: could engineering measurements be used to determine the best weight combination, and would this agree with the archers' perceptions?

This particular topic was selected for the first study because the stabilisation system in archery has a well-defined scope, so the definition of objective and subjective metrics was simplified. The weight distributions were defined considering the commercially available weights that are commonly used by barebow archers. A total of eleven weight configurations were tested. Subjective and objective metrics were defined considering the particular requirements of the analysed problem, the best weight distribution on the bow was decided considering the collected subjective metrics, the objective metrics were measured, and the correlations between performance, design details and user sensations were found. The study of the correlations provided insights into the problem, allowing the definition of the best weight distribution for the barebow style, from both the engineering and the archers' points of view.

Seven archers from the Archers of the Zoo Lake Club participated in the study. Of these, two were classified as Intermediate and five as Advanced archers. The classification is based on the guidelines defined in the club [83]: an Intermediate archer is an archer who has finished the six-month Beginner program and started to compete in regional championships. An Advanced archer is an archer with more than four years of training and who participates in national championships.

3.2. Methodology

For the first study of this work, an exploratory sequential mixed methods design was used, starting the research with a qualitative research phase exploring the views of participants. The data were then analysed and the information was used to build into a second, quantitative phase (QUAL → QUAN approach) [1] [2].

The qualitative (QUAL) research tool

Four subjective metrics were chosen for the research: weight balance, perceived vibrations, dynamic behaviour and overall quality of the tested eleven weight configurations. The decision about the subjective metrics was based on the experience of the researcher as an archer[7], considering the role of a stabilisation system, and what an archer can perceive on shooting, and what would be possible to measure in the quantitative part of the research. The subjective metrics were collected by testing the eleven configurations with seven archers belonging to the Archers of Zoo Lake Club. The archers were chosen with a purposive sampling (all of them were archers), and with a convenience/opportunistic sampling (all of them belonged to the Archers of Zoo Lake Club) [1] [2]. Unfortunately, a group of seven archers is not enough to reach saturation. According to Tracy [11], if the goal is to describe a shared perception, belief, or behaviour among a relatively homogeneous group, then a sample of twelve will likely be sufficient for saturation. Seven archers were all the available archers at the time of testing, and with the necessary characteristics: barebow archers of level intermediate or advanced. The tests of the different configurations were executed in a random order for each archer, creating the necessity of covering the weights on the central and lower attachments so that the archers could not see the weight configuration being tested. A questionnaire was administered to the archer after the test of each configuration to collect the subjective metrics. The questionnaire was specifically designed to be as precise as possible in asking the right questions about the subjective metrics to collect meaningful answers. The questions were compiled using archery jargon to pinpoint specific sensations associated with the shooting. The questionnaire was tested and refined by the three coaches of the Archers of the Zoo Lake Club. The questionnaire is available in Appendix E.

Several confounding variables [1] [2] [11] [12] were considered and controlled:

- Atmospheric conditions: the tests were executed within a week, with constant atmospheric conditions.
- Archers' experience: all archers admitted to the tests were highly proficient archers in the barebow style and in the sport of archery.

[7] Mr F. Pietra has been practicing archery since November 2016. He has graduated from the Beginner and Intermediate course of the Archers of the Zoo Lake Club, and has been regularly competing in archery championships since 2020. In 2022 he become an archery coach within the South African National Archery Association (SANAA). He is in charge of the Intermediate course in the Zoo Lake Club and he is coaching Mr Connor Young, member of the South African Olympic Team. In 2024 he become an archery judge within World Archery Federation (WA).
Next to his archery carrier, Mr Pietra is an academic working as a lecturer in the School of Mechanical, Industrial and Aeronautical Engineering at the University of the Witwatersrand, Johannesburg. He holds a MSc in Aerospace Engineering, and a MEng in Mechanical Engineering.

- Jargon, interpretation of the questions: all archers are from the same club, meaning that all have undergone the same training and use the same jargon to talk about archery.
- Personal relationship with the researcher: all archers know the author personally, and normally train under his direction.
- Bias of the researcher: no conscious biases were introduced into the study because the author is a recurve archer, not a barebow one; therefore, he has no prior preconceptions of what a barebow stabilisation system should be.
- Stamina and strength of the archers: the necessity of changing from one configuration to another implied some time between tests, more than enough to guarantee a rested archer during testing.

The quantitative (QUAN) research tool

The objective metrics considered in the study were the vibration of the bow evaluated at five positions along the bow, the motion of the bow on shooting, and the precision of the various configurations measured as the score of thirty arrows. For all the previously defined objective metrics, the independent variable was the eleven weight configurations. The thirty-arrow score metric was initially chosen in line with standard practice for evaluating performance in archery, but it was subsequently challenged during the review phase of the paper.

The data were collected using a single archer (the author) to shoot all the tested configurations, with three shots taken per configuration. The use of an archer was preferred over the use of the shooting rig because of the shooting technique. In the standard shooting technique, the bow is allowed a horizontal movement on the release of the arrow, so the bow is free to vibrate without constraints. The shooting rig securely clamps the bow to the structure, meaning that the vibration of the bow would be completely altered by the constraint compared to the normal vibration of the bow on shooting. The archer also used a clicker (refer to chapter 2.3) to guarantee uniformity in the draw for all tests. The objective metrics were collected in the Archery Laboratory, North West Engineering Building, University of the Witwatersrand, Johannesburg. The Archery Laboratory is a facility designed and built by the author to study and measure the performance of archery equipment.

3.3. Contribution of the author to the first paper and contribution to knowledge

The journey that led to the first publication started in mid-2019 when the author submitted his original idea for a PhD degree to Prof. Frank Kienhöfer who undertook to supervise the author's PhD studies. The PhD proposal was presented in November 2019 to the School of Mechanical, Aeronautical and Industrial Engineering (MIA School), University of the Witwatersrand, Johannesburg. The PhD proposal was accepted with minor corrections. The next two years were dedicated to designing, financing and

building the Archery Laboratory, a facility dedicated to the study of archery. The author designed the equipment inside the Archery Lab and secured funds from the Faculty of Engineering and the Built Environment and the MIA School to build the laboratory. In mid-2021, the author decided upon the first study subject and started the initial testing and data analysis. In January 2022, he obtained Ethics clearance from the University of the Witwatersrand (Appendix D). The author designed and administered the questionnaire to collect the subjective metrics of this study. The questionnaire is available in Appendix E. Also, in January 2022 it was decided to change the supervisor to Profs. Philip Loveday and Robert Reid both from MIA School. Through the interaction with the new supervisors, new tests were designed and executed. The collaboration with Profs. Loveday and Reid was fundamental to refine the methodological approach to the problem and to understand the physics behind the collected data. Through continuous interaction between the author and the supervisors, the data analysis provided a deep understanding of the problem and the first step in applying the research methodology. The writing of the paper was completed by the author, with the paper ready for submission by August 2022 and published online in February 2023.

Regarding the paper's contribution to knowledge, this study was a significant step in the direction of proving the effectiveness of a mixed research methodology in the evaluation of the relationship between performance (engineering measurements), equipment design and archer sensations on shooting, for the sport of archery.

The first paper with the title '*Analysis of preferred weight configuration for barebow shooting style*' was published in Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology on the 14th of February 2023 (online publication). The paper is available at the following link:

https://journals.sagepub.com/doi/10.1177/17543371231155510?icid=int.sj-full-text.citing-articles.2#:~:text=The%20results%20show%20that%20the,and%20lower%20attachment%20points%2C%20respectively.

3.4. First journal paper: Analysis of preferred weight configuration for barebow shooting style

The following paper is in the "accepted manuscript" version, maintaining its original structure as submitted for publication. It is presented with single-line spacing to distinguish it from the rest of the thesis. The first page of the published version of the paper is available in Appendix A. The paper is reproduced under the terms of Sage's Author Archiving and Re-Use Guidelines. Please see Appendix G for details.

Title

Analysis of preferred weight configuration for barebow shooting style

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Abstract

The barebow archery shooting style limits the stabilisation system to weights connected to the riser, which is the central part of the bow. No scientific study is available to guide the barebow archer in the choice of the best weight configuration. In the following work, a human-centred methodology was developed to address this problem from both a scientific and user-oriented perspective. The proposed methodology is based on subjective metrics (archers' sensations using the equipment), objective metrics (measurable quantities) and precision. The study sought a correlation between the subjective and objective metrics to provide insight into the problem of configuring a bow.

Eleven weight configurations were considered. The vibration was measured at five positions on the bow and the 3D dynamic motion was measured using an inertial measurement unit. Seven archers completed a questionnaire to evaluate the subjective shooting sensations.

The results show that the two best weight configurations are the 250 g – 200 g and the 350 g – 200 g, at the central and lower attachment points, respectively. A strong correlation exists between the vibration level of the bow and the feeling archers associated with the shooting, and between the dynamic motion of the bow and the comfort of the shooting. No correlation was found between the vibration time and the physical sensations felt by the archers. Determining the influence of the weight configuration on shooting accuracy, with statistical significance, would require an impractically large number of arrows to be shot for each weight configuration.

A new methodology was developed to correlate the archers' physical sensations to measurable parameters and this was applied to understand the barebow weight selection problem. This

methodology could be further developed to correlate additional subjective and objective metrics. An understanding of these correlations would allow objective metrics, which can be simulated in the design process, to be used to ensure satisfaction of subjective metrics by the final design.

Highlights

- Subjective measures of different weight configurations were obtained from a questionnaire to establish the preferred weight configuration of the bow
- 3D motion and vibrations of the bow were measured with different weight configurations
- Measurements were processed to yield objective measures that correlate with subjective measures
- Insight was gained into the archer's perception of engineering measures, which could aid in equipment development.

Keywords
Archery, barebow, barebow weight configurations, subjective metrics, objective metrics, correlation.

List of Notation

CoG	Centre of gravity
DAQ	Data acquisition system
MSV	Mean Squared value
P2P	Maximum to Minimum Difference
RMS	Root Mean Squared value
WA	World Archery Federation
r	Pearson correlation coefficient
V	Percentage of proportion of predictable variability

1. Introduction

The World Archery Federation (WA) is the international federation for the Olympic and Paralympic sport of archery [1]. The WA recognises three styles for archery: the recurve bow - which is the style used at the Olympic games, the compound bow and the barebow style [2]**.** Recurve and barebow archers use the same type of bow, but in the barebow style the sight and the clicker are not allowed and the V-Bar stabilisation system of the recurve style is limited to simple weights attached to the riser (the central, rigid part of the bow) [3].

The main functions of an archery stabilising system (weights added to the bow to stabilise its motion during shooting) are control of the displacement and the rotation of the bow during the aiming phase, control of the vibrations [4], and control of the dynamic action of the bow on string release [5][6]. This set of requirements defines the shape of the stabilisation system.

The dynamic behaviour of the bow on release is related to the weight distribution of the stabilising system (weight configuration) in comparison to the position of the centre of gravity (CoG) of the bow. A Cartesian coordinate system is defined as centred on the pressure button [7] (Figure 1). The X axis follows the direction of the arrow, parallel to the ground. The Y axis lies on the plane of the bow (the plane created by the string and the middle section of the limbs), upward. The Z axis is perpendicular to the XY plane and on the right (as seen by the archer).

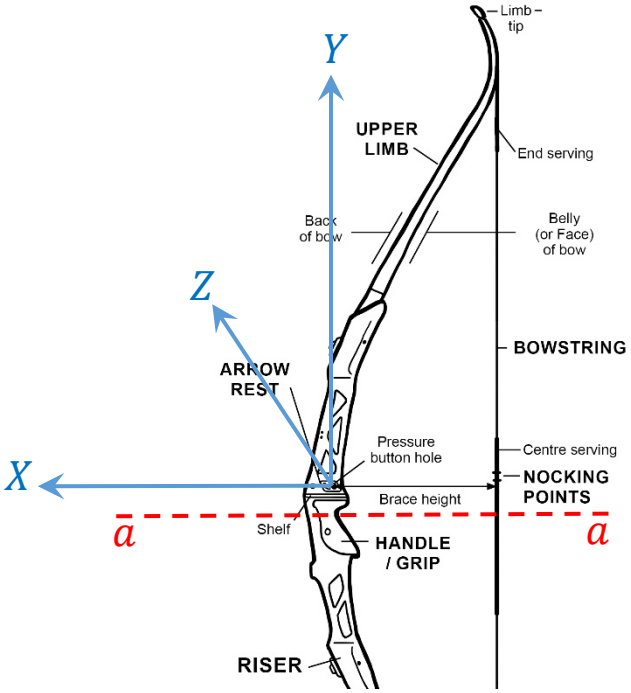


Figure 1 – Global coordinate system [8]

Without stabilisation, the CoG of the bow is positioned at the same height as the handle (line $a - a$), behind the handle on the XY plane. On release, the bow will rotate around the $+Z$ axis (positive rotational direction according to the right-hand rule) [9].

The stabilisation system is designed to move the CoG ahead of the handle and along the $-Y$ direction. On release, the bow will initially move in the X direction, then the riser will be caught by the finger sling (a piece of string that connects the index and the thumb of the archer) and will rotate around the $-Z$ axis [9]. This is the desired dynamic behaviour of the bow because the movement in the X direction does not affect the launching of the arrow and the $-Z$ axis rotation will move the upper limb away from the archer. A bow will behave reasonably well with the CoG within about four inches (10 cm) forward of and below the handle [9].

In the barebow style, the stabilisation system is limited to weight(s) and/or dampeners that may be added to the riser (WA Rulebook no. 3 published on 7/3/2022 [1]). Within this rule, it is possible to

attach weights to the riser in two different positions: the centre attachment point (Figure 2, 'A') and the lower attachment point (Figure 2, 'B'). The upper attachment point (Figure 2, 'C') is never used because the CoG of the bow needs to be moved in the X and $-Y$ directions [9]. The stabilisation system allowed for the barebow style helps to stabilise the displacement of the bow in the $-Y$ direction and its rotation around the $+X$ axis, but it has little to no effect on stabilisation of the rotations around the $+Y$. Since the 2022 version of the WA rules, dampeners are permitted in the barebow style [1]. In this paper, the best weight configuration will be studied without considering dampening. In a future study, possible damping devices and the effects of damping will be studied.

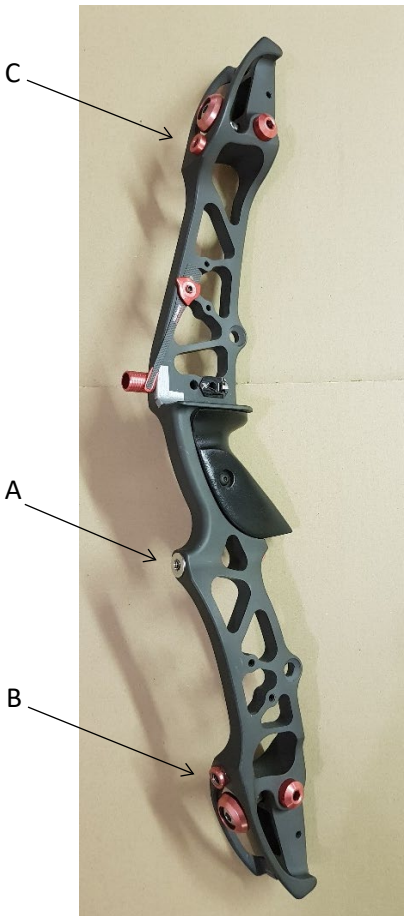


Figure 2 - Riser Gray AIX. A, B and C are the attachment points

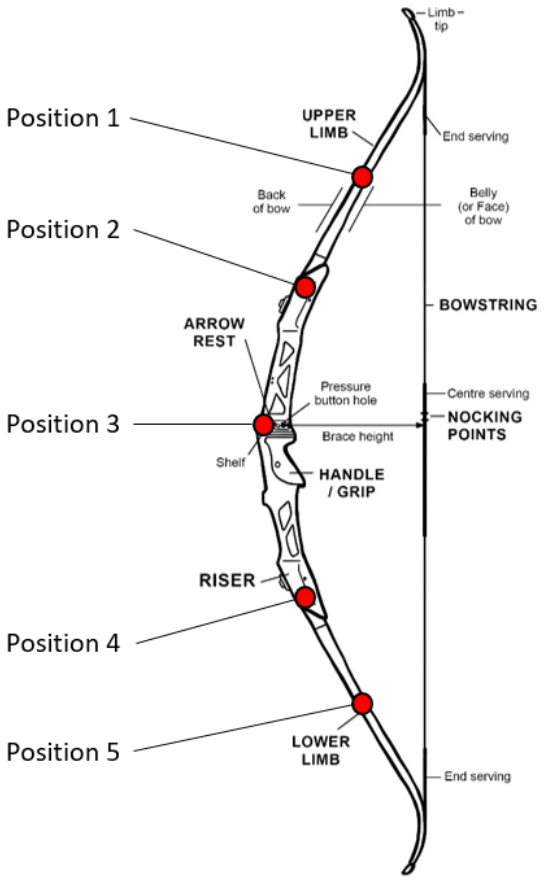


Figure 3 - Positioning of the accelerometer on the bow

2. Methods

The following work develops a methodology using an archer-centred approach and a scientific approach to define the best weight configuration for the barebow shooting style. The problem with the design of sporting equipment is that it cannot be based purely on performance, because the user's experience in using the equipment is a necessary part of the design. Considering archery, archers are not interested in pure performance (efficiency of the bow, speed of the arrow, etc.) but in the precision of their equipment. The best weight configuration will then be decided by considering performance (objective metrics), the personal experience of the archer (subjective metrics) and the effect that the weight configuration has on precision (bow-archer interaction).

To analyse the barebow weight distribution problem, it was decided to consider subjective metrics, objective metrics and precision. The subjective metrics were the physical sensations associated with shooting: the static behaviour of the bow in the aiming phase, and on shooting, the level of perceived vibrations and the dynamic behaviour of the bow. A questionnaire was prepared and administered to collect the archers' physical sensations on release.

The objective metrics were the vibrations of the bow during the shooting and the dynamic behaviour of the bow on release. Eleven weight configurations (Table 1) were tested for vibrations in five areas of the bow: upper and lower limb, upper and lower limb pocket on the riser and centre of the riser (Figure 3).
The precision of each weight configuration was measured by the score of 30 arrows. The arrows were shot over a distance of 50 m, at a WA – 122 cm, 10-ring target. The distance and target size were chosen according to the standards for a WA barebow competition.

3. Experimental Set-Up

The riser used in the experiments was the Gray AIX 2019 [10], which is considered within the South African barebow community, to be one of the best risers for this style [11]. The limbs were the Win&Win Limbs Wiawis NS Wood (long version, 32 lb nominal poundage) [12]. The weights were the Gas Pro Barebow Weights, with nominal weights of 350 g, 250 g and 200 g [13]. The arrows were shot using the standard hooking for barebow style: the three-fingers-under-the-arrow style. For consistency between the tests, gap-shooting was adopted as the aiming style [14].
The bow was set up for the recurve style and tuned using the procedure described by Kaminsky [15]. The eleven weight configurations tested are listed in Table 1:

Table 1 - Weight configurations

	V-Bar	Naked	200-0	250-0	350-0	200-250	200-350	250-200	250-350	350-200	350-250
Weight at Centre Point A [g]	842.35	---	200	250	350	200	200	250	250	350	350
Weight at Lower Point B [g]	---	---	---	---	---	250	350	200	350	200	250
Bow Weight [g]	2730.93	1888.58	2101.40	2152.86	2253.00	2365.68	2465.82	2365.68	2517.28	2465.82	2517.28

4. Subjective metrics: the questionnaire

A questionnaire was administered to seven archers from Archers of the Zoo Lake Club, Johannesburg, South Africa. The archers were classified as two Intermediate and five Advanced archers (proficiency evaluations based on the Archers of the Zoo Lake Club guidelines [16]). The archers were asked to evaluate the proposed eleven weight configurations using a numerical scale ranging from "*very bad*" (numerical score 1) to "*very good*" (numerical score 5). The questionnaire was divided into three questions exploring the archer's sensations for three different phases of the shooting, namely:

- The weight balance of the bow during the drawing and aiming phases
- The vibrations of the bow during the shooting of the arrow
- The dynamic behaviour of the bow after the shooting of the arrow

During the administration of the questionnaire, the weights on the central and lower attachments were covered so that the archers could not see the weight configuration being tested. The averaged collected data are reported in Appendix A.
The data analysis shows the complexity of this problem: the same weight configuration scores differently across the proposed questions. Nevertheless, some general conclusions can be drawn from the overall quality analysis. Adding weight to the riser is beneficial from the shooting sensation point of view. A two-weight configuration is better than the single-weight configuration, with the heaviest weight attached to the centre attachment point (closer to the CoG). Unfortunately, increasing the weight of the stabilisation system has negative consequences on the archer's fatigue during competition shooting. The four weight configurations 200–250, 250–200, 350–200 and 350–250 (refer

to Table 1) were the top-rated configurations. Because the archers decided on the best weight configurations based on their user experience, a baseline is available to correlate the subjective and objective metrics.

5. Objective metric: vibrations

The vibrations associated with the shooting phase were recorded using a triaxial accelerometer from PCB Piezotronics [17] and a data acquisition (DAQ) system from National Instruments [18]. The nominal signal rate was defined as 12,000 Hz for 180,000 samples (15 s measurement duration).
The three acceleration signals were captured at five different positions on the bow (Figure 3), with six tests for each position of the accelerometer. Position 1 was defined on the upper limb, at a distance of 350 mm from the end of the limb (main bolt attachment area) along the limb itself. Position 2 was defined on the riser, 40 mm from the top of the riser. Position 3 was defined on the riser, next to the secondary pressure button's hole. This is close to the archer's hand position on the bow. Position 4 is symmetric to Position 2 but on the lower section of the riser. Position 5 is symmetric to Position 1 but on the lower limb.
The three acceleration signals shown in Figure 4 were captured by the accelerometer in Position 1 for the Naked weight configuration (refer to Table 1). The data from the other weight configurations and measured positions have the same form. The reported accelerations are in g (Earth's gravity acceleration).

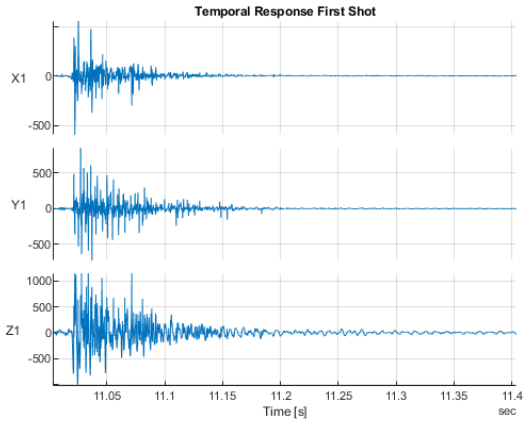


Figure 4 – Recorded 3-axis acceleration signal, Position 1, Naked configuration, first shot. Y scale in g

The data are reported in the local coordinate system defined by the accelerometer (X axis aligned with the limb, positive upward; Y axis perpendicular to the limb's middle line and positive on the left, looking at the back of the limbs; Z axis perpendicular to the back of the limb, positive in the backward direction).
The signal is non-zero from about 11.02 s to 11.184 s in the X and Y directions (0.164 s duration) and to 11.31 s in the Z direction (0.29 s duration). The maximum peak is registered in the Z direction with an acceleration equal to 1150.2 g. This result is comparable to the values of the acceleration of the arrow on release from the literature [19]. The vibration in the local Y direction is expected: the mechanics of the barebow release implies an initial acceleration of the string in the local Y direction while accelerating in the XZ plane [20].
The power spectrum of the signals was calculated, but the result was the superposition of multiple excitation frequencies with peaks up to 4,000 Hz. Given the complexity of the signal, an analysis based on a statistical approach was adopted. The following signal statistics were calculated [21]: the *Maximum to Minimum Difference* (P2P), which is a measure of the maximum amplitude of the signals, dimension g; and the *Root Mean Squared value* (RMS) of the signal, which is the square root of the *Mean Squared value* (MSV) of the signal, dimension g. The MSV is defined as the average squared value of the signal over the time interval. P2P and RMS data were averaged across the six shots.

Because the five positions of the accelerometers have different local coordinate systems, the data were rotated into the global coordinate system defined in Figure 1. The data are collected in Appendix B.

6. Damping and duration of the signal

The time signals for the 11 weight configurations show that the bow is damped (Figure 4). Sources of damping are the friction between the string and the limbs, the drag of all the moving parts through the air, the hysteretic material damping of the entire bow system and the archer's hand on the handle. The analysis of the damping ratios associated with the resonant modes in vibration signals did not show a strong correlation with the perceived quality of the shooting experience. It was hypothesised that the archer perceives the effect of the damping in terms of the amplitude of the signal (P2P) and the time necessary for the bow to stop vibrating.

The time necessary for the bow to stop vibrating was calculated by imposing zero amplitude for any vibration amplitude less than 15 g, and evaluating the time between the first and the last non-zero reading. The analysis of the vibration duration time did not show a strong correlation with the perceived quality of the shooting experience but for Position 1 (refer to Table 3).

7. Vibration analysis

The archers' perceptions of the level of vibration of the bow (Quality) are reported in Table 2. The Quality was compared with the signal statistics by calculating the Pearson correlation coefficient (r) and the percentage of proportion of predictable variability ($V = r^2$) [22] as shown in Table 3. A Pearson correlation coefficient of $r > 0.5$ indicates a direct correlation, while $r < -0.5$ indicates an inverse correlation. If a direct or an inverse correlation was found between the data and the perceptions, then the data were highlighted in bold. Table 3 reports the comparison for Position 1. The variability V is a measure of the proportion of total variability in one variable that is predictable from its relationship with the other variables [22] or, in other words, it gives an idea of the percentage of data points close to the line formed by the regression equation.

Table 2 – Vibration level perceived by the archers

Vibrations		
Weight Conf.	**Results**	**Evaluation**
Naked	1.0	Very Bad [1]
200-0	1.0	Very Bad [1]
200-250	4.0	Good [4]
200-350	3.0	Acceptable [3]
250-0	2.0	Bad [2]
250-200	5.0	Very Good [5]
250-350	3.0	Acceptable [3]
350-0	2.0	Bad [2]
350-200	5.0	Very Good [5]
350-250	4.0	Good [4]
V-Bar	5.0	Very Good [5]

Table 3 - Vibration analysis, Position 1

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Time [s]
Naked	1	1537.19	1941.99	1535.11	2913.90	127.94	53.41	64.87	153.07	0.5349
200-0	1	1570.45	2034.45	1241.77	2854.34	135.11	59.20	64.80	161.12	0.5361
250-0	2	1509.72	1796.65	1960.51	3057.91	121.96	55.75	68.04	150.37	0.5916
350-0	2	1480.82	1899.79	1583.94	2882.86	121.69	56.84	69.85	151.39	0.5348
200-350	3	1491.34	1979.07	1717.90	3015.29	120.57	57.83	60.11	146.61	0.5843
250-350	3	1481.31	2147.16	1237.94	2887.40	138.19	62.94	64.83	165.10	0.5607
200-250	4	1516.43	2147.86	1221.74	2899.22	141.27	64.88	66.13	168.94	0.4516
350-250	4	1489.04	2078.48	1341.13	2887.21	122.15	59.71	62.76	149.75	0.4743
250-200	5	1447.45	2026.99	1210.04	2769.12	118.06	56.30	58.38	143.23	0.5377
350-200	5	1527.29	2069.06	1211.00	2842.55	122.87	58.77	61.99	149.64	0.4502
V-Bar	5	1526.04	2088.97	1140.50	2827.25	134.48	63.20	47.36	155.96	0.4250

r	-0.412	**0.550**	**-0.547**	-0.480	-0.087	0.469	**-0.625**	-0.180	**-0.628**
V [%]	17.0	**30.3**	**29.9**	23.0	0.8	22.0	**39.1**	3.3	**39.4**

Although Positions 1 (shown in Table 3) and 2 show a limited level of correlation, Position 3 does not show any correlation, while Positions 4 and 5 show a very limited correlation (the complete set of data is reported in Appendix B). All highlighted correlations are negative, indicating that reduced vibration is associated with an improved sensation. It is interesting, however, that the correlation between the Quality and P2P in Y direction is positive ($r = 0.550$): the perceived quality increases with the amplitude of the vibration in the Y direction. A possible explanation is that the archer is not sensitive to the vibration in the Y direction and the Pearson coefficient is, in this case, a mathematical occurrence and not a causality occurrence.

The limited correlation between Quality and metrics is of concern. The suggested explanation is that the archer perceives the vibration of the bow in two different ways: airborne sound and mechanical vibration of the riser. The sound is due to the high-frequency component of the vibrating part of the bow, mainly the string and the limbs. The mechanical vibration of the riser is perceived through the archer's fingers, wrist, arm and shoulder and it is a low-frequency vibration. According to the literature, the human arm is sensitive to vibrations up to 500 Hz [23] [24] [25] [26] [27] so the original vibration signal was filtered with a lowpass filter at 500 Hz. According to Dong et al. [27], along with P2P and RMS, a new metric could be introduced to evaluate the intensity of the vibrations acting on the human arm: damage, as defined in the engineering definition of fatigue. The peaks in the filtered signal were counted with the Rainflow counting method and the damage was calculated as the average of the sorted bin edges multiplied by the number of occurrences. Although this number is not immediately comparable with the engineering definition of damage in fatigue, it could give an idea of the accumulating damaging nature of the signal.

The correlations for the filtered signal are reported in Tables 4a to 4e, where Damage X, Y and Z is the damage in the different directions, and Damage is the root sum of squares of the previous values.

Table 4a - Vibration analysis with 500 Hz filter, Position 1

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Damage X	Damage Y	Damage Z	Damage
Naked	1	1361.15	1140.86	504.99	1846.43	96.73	70.07	32.10	123.68	19667	14443	7728	25595
200-0	1	1352.90	1176.50	477.06	1855.29	103.53	76.20	27.44	131.45	24457	17024	6215	30440
250-0	2	1320.90	1224.34	473.68	1862.30	108.90	83.92	28.93	140.50	27046	20388	6755	34537
350-0	2	1263.10	1193.36	455.44	1796.37	102.43	80.52	30.73	133.86	22366	18113	7730	29801
200-350	3	1269.73	1122.05	770.75	1861.52	100.82	73.52	37.21	130.21	20956	15544	7383	27116
250-350	3	1230.40	1155.39	511.49	1763.64	92.37	71.23	27.50	119.84	16509	13691	5900	22244
200-250	4	1292.92	1103.69	696.13	1836.95	100.03	71.98	51.55	133.59	19420	14445	8017	25497
350-250	4	1233.73	1165.71	524.19	1776.44	100.42	76.10	28.69	129.22	22217	16522	6458	28430
250-200	5	1233.77	1150.80	691.47	1823.37	96.07	74.79	35.43	126.80	18787	15416	8321	25688
350-200	5	1248.33	1165.86	523.87	1786.61	94.55	72.43	27.84	122.31	19460	15052	6305	25397
V-Bar	5	1205.30	1160.20	371.84	1713.79	110.24	82.66	25.36	140.10	29282	20445	5553	36143

r	**-0.824**	-0.297	0.220	**-0.575**	-0.125	-0.009	0.129	-0.035	-0.079	-0.044	-0.099	-0.071
V [%]	**67.8**	8.8	4.9	**33.1**	1.6	0.0	1.7	0.1	0.6	0.2	1.0	0.5

Table 4b - Vibration analysis with 500 Hz filter, Position 2

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Damage X	Damage Y	Damage Z	Damage
Naked	1	216.16	183.40	313.97	423.01	14.54	14.49	28.85	35.41	4370	3022	6405	8322
200-0	1	188.01	172.64	303.10	396.26	13.73	11.32	22.83	28.95	4106	2297	4895	6789
250-0	2	173.92	169.42	313.76	396.74	12.31	10.65	22.53	27.79	3263	1923	4660	6005
350-0	2	185.45	168.81	321.04	407.38	13.01	10.37	22.05	27.62	3710	1881	4490	6121
200-350	3	189.60	140.39	299.30	381.10	12.94	8.88	21.19	26.37	2999	1589	4528	5659
250-350	3	177.43	137.60	303.40	377.45	12.91	8.49	20.97	26.05	2925	1503	4458	5539
200-250	4	169.76	150.06	283.61	363.00	11.99	8.70	20.70	25.45	2653	1563	4420	5387
350-250	4	179.36	146.41	303.86	382.01	12.58	8.58	21.64	26.45	3069	1519	4465	5627
250-200	5	162.70	154.44	290.39	366.95	12.05	8.77	21.18	25.90	2889	1628	4608	5677
350-200	5	171.97	149.54	306.26	381.75	12.05	8.73	21.85	26.44	2923	1579	4590	5666
V-Bar	5	184.96	147.14	309.73	389.61	13.64	8.88	21.39	26.88	4262	1612	4520	6418

r	**-0.657**	**-0.720**	-0.471	**-0.732**	**-0.605**	**-0.787**	**-0.611**	**-0.676**	**-0.505**	**-0.757**	**-0.558**	**-0.619**
V [%]	**43.2**	**51.8**	22.2	**53.6**	**36.6**	**62.0**	**37.3**	**45.8**	**25.6**	**57.3**	**31.1**	**38.3**

Table 4c - Vibration analysis with 500 Hz filter, Position 3

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Damage X	Damage Y	Damage Z	Damage
Naked	1	314.35	54.39	176.38	364.53	19.38	4.05	13.60	24.02	3344	1005	2873	4522
200-0	1	294.69	40.58	174.90	345.08	18.02	3.50	13.18	22.60	3055	885	3772	4934
250-0	2	292.76	41.35	160.36	336.35	17.42	3.71	12.98	22.04	2818	945	3343	4474
350-0	2	280.50	41.84	182.06	337.02	17.32	3.52	13.18	22.05	2855	848	3627	4693
200-350	3	292.24	47.79	139.80	327.46	18.07	3.53	10.17	21.04	2857	727	2486	3856
250-350	3	279.07	48.16	145.95	318.59	17.81	3.43	10.25	20.83	2838	748	2311	3735
200-250	4	285.80	44.94	135.21	319.35	17.32	3.28	9.86	20.19	2645	688	2420	3650
350-250	4	270.66	48.74	151.16	313.81	16.73	3.87	10.40	20.08	2600	925	2350	3625
250-200	5	290.65	44.94	133.23	322.87	17.49	3.29	9.82	20.33	2743	736	2367	3697
350-200	5	277.41	49.30	124.68	308.11	17.23	3.64	10.45	20.47	2723	866	2679	3917
V-Bar	5	260.43	55.24	144.82	303.06	14.19	5.20	10.55	18.43	2333	1226	2718	3786

r	**-0.680**	0.337	**-0.866**	**-0.895**	**-0.643**	0.195	**-0.860**	**-0.899**	**-0.817**	-0.022	**-0.684**	**-0.841**
V [%]	**46.2**	11.4	**75.1**	**80.2**	**41.4**	3.8	**74.0**	**80.8**	**66.8**	0.0	**46.8**	**70.6**

Table 4d - Vibration analysis with 500 Hz filter, Position 4

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Damage X	Damage Y	Damage Z	Damage
Naked	1	326.11	212.73	219.08	446.77	24.21	17.45	17.57	34.63	5678	3649	5418	8655
200-0	1	374.37	230.84	160.28	468.11	23.21	14.84	12.32	30.17	4733	2923	2552	6120
250-0	2	397.54	234.36	164.16	489.80	24.05	15.27	11.60	30.76	5005	2948	2367	6272
350-0	2	400.53	234.31	151.22	488.06	22.71	14.12	11.19	28.99	4678	2665	2198	5815
200-350	3	196.47	183.03	335.09	429.40	13.46	11.28	16.52	24.11	2920	2165	3035	4735
250-350	3	207.57	183.85	343.10	441.14	14.34	11.66	16.48	24.76	3060	2300	3070	4907
200-250	4	204.52	179.42	328.05	426.18	13.75	11.02	15.42	23.42	2990	1989	2897	4614
350-250	4	237.30	186.31	386.28	490.14	14.97	11.23	17.49	25.61	2995	2160	3008	4762
250-200	5	268.52	198.24	299.59	448.51	18.11	12.48	15.36	26.83	3213	2478	2943	5012
350-200	5	250.08	191.79	372.78	488.15	15.70	11.25	16.47	25.39	3173	2004	2888	4735
V-Bar	5	374.19	231.83	145.86	463.73	22.11	13.06	9.62	27.42	4460	2498	2063	5513

r	-0.446	-0.447	**0.505**	-0.037	**-0.560**	**-0.746**	0.096	**-0.690**	**-0.681**	**-0.742**	-0.343	**-0.705**
V [%]	19.9	20.0	**25.5**	0.1	**31.3**	**55.7**	0.9	**47.6**	**46.4**	**55.1**	11.8	**49.7**

Table 4e - Vibration analysis with 500 Hz filter, Position 5

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Damage X	Damage Y	Damage Z	Damage
Naked	1	1404.81	748.51	429.63	1648.74	109.98	56.86	32.94	128.12	22914	11967	7638	26955
200-0	1	1599.55	813.44	385.30	1835.40	110.29	55.41	27.54	126.46	25053	12406	5688	28529
250-0	2	1562.12	909.88	432.52	1858.81	102.85	58.72	28.47	121.81	20594	12075	5985	24612
350-0	2	1507.70	982.06	476.47	1861.35	104.11	63.27	29.63	125.38	21859	13352	6691	26474
200-350	3	1296.82	729.60	384.12	1536.75	95.27	52.72	27.38	112.28	15517	8992	6488	19072
250-350	3	1311.71	832.30	358.37	1594.28	96.65	57.28	24.65	115.02	15878	10273	6053	19856
200-250	4	1417.25	701.28	316.94	1612.71	100.51	49.75	22.14	114.32	17008	8636	5520	19857
350-250	4	1190.78	1059.15	376.96	1637.63	94.44	72.09	29.29	122.36	17727	13823	7189	23601
250-200	5	1378.22	812.89	357.33	1639.50	95.17	54.78	22.49	112.09	15997	9719	5478	19503
350-200	5	1227.47	1015.92	455.85	1657.28	88.91	63.62	24.34	112.01	14800	11136	5153	19225
V-Bar	5	1251.47	1197.41	388.67	1775.11	93.84	68.03	27.76	119.19	21347	14542	5978	26513

r	**-0.719**	0.422	-0.322	-0.388	**-0.900**	0.285	**-0.644**	**-0.752**	**-0.694**	-0.132	-0.489	**-0.608**
V [%]	**51.7**	17.8	10.4	15.1	**81.0**	8.1	**41.4**	**56.5**	**48.2**	1.7	23.9	**36.9**

The data analysis shows a good correlation between the filtered signal metrics and the perceived vibrations for Positions 2 to 5, with high values of the Pearson coefficients and medium to high values of the variances. The archers are sensitive to the amplitude of the vibration and the energy content of the vibration. The damage shows a good level of correlation between the calculated value and the perceived quality. Interestingly, in Position 4 the Pearson coefficient for the peak-to-peak in the Z direction is positive (the greater the amplitude of vibrations, the better the feeling). It is suggested that a positive correlation does not imply causality but means that the archer is not sensitive to the specific metric.
The weight configurations previously identified (350–200 and 250–200 rated "*Very good*"; 200–250 and 350–250 rated "*Good*") consistently show the lowest level of vibrations according to the proposed metric and are suggested as the best weight configurations.

8. Bow Dynamic Behaviour analysis

The Arduino MPU6050 Accelerometer and Gyroscope Sensor was used to compare the recorded dynamic behaviour of the bow with the recorded archers' sensations. The Arduino MPU6050 sensor recorded the displacement of the bow in X, Y and Z directions as well as the rotation of the bow in roll, pitch and yaw (rotations about the global X, Z and Y axis respectively) and it was positioned next to the button in Position 3 (Figure 5).

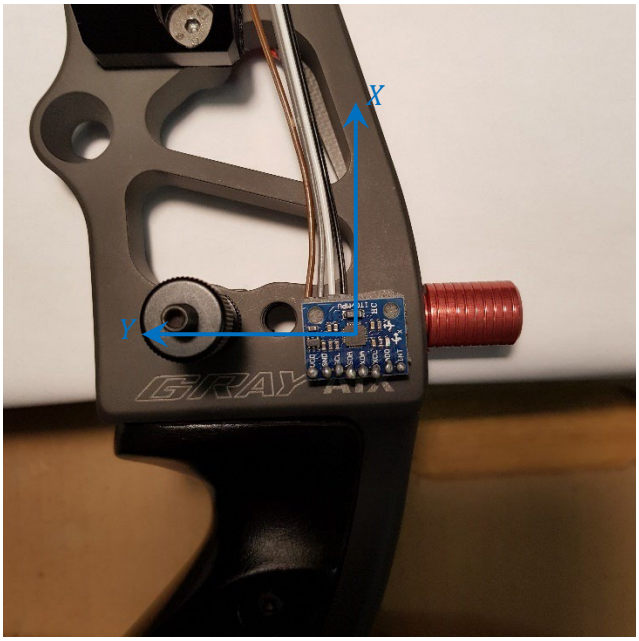


Figure 5 - Arduino MPU6050 sensor and the local coordinate system

Four shots for each weight configuration were recorded and averaged for both the recorded values and the absolute of the recorded values. The Pearson correlation coefficient (r) and the percentage of the proportion of predictable variability ($V = r^2$) [22] were calculated to correlate the perceived quality with the recorded metrics. The results are shown in Table 5. The data analysis shows that the archer evaluates the dynamic behaviour of the bow considering just the displacement in the global Z −axis, and the pitch (rotation around Z −axis). These findings could be explained considering the mechanics of the bow on release and how the bow interacts with the archer's hand on release. Some displacement of the bow in the X direction is expected so the archer just ignores this component of the displacement, while the displacement in the Y direction is normally lost in the rotation of the bow. The roll is also difficult to perceive, due to the proximity of the hand and CoG in Position 3. It is instead quite interesting that the archer is not sensitive to the yaw (rotation around Y −axis).

Table 5 - Dynamic behaviour of the bow. Delta X, Y and Z are the displacements in the respective global directions. Roll is the rotation around the X-axis, Pitch is the rotation around the Z-axis and Yaw is the rotation around the Y-axis

		Delta X [mm]		Delta Y [mm]		Delta Z [mm]		Delta Roll [°]		Delta Pitch [°]		Delta Yaw [°]		Avg. Displ.	Avg. Rot.
Config.	Quality	Abs. Avg.	Avg.	Abs. Avg.	Avg.	Abs. Avg.	Avg.	Abs. Avg.	Avg.	Abs. Avg.	Avg.	Abs. Avg.	Avg.	[mm]	[°]
Naked	2.0	34.5	-34.5	118.7	118.7	139.2	139.2	7.9	-3.9	108.9	108.9	20.3	20.3	197.4	111.3
200-0	2.0	23.9	-10.5	49.9	29.4	43.9	43.9	12.9	-10.5	89.2	89.2	26.8	26.8	77.8	96.3
250-0	2.0	31.6	-3.5	90.5	45.9	60.9	60.9	35.4	-35.4	62.3	62.3	3.7	1.8	124.1	73.5
350-0	3.0	38.1	-4.0	119.7	119.7	15.6	11.2	23.1	-18.5	64.6	64.6	4.5	4.1	128.8	71.8
200-250	3.0	50.3	-9.1	85.0	47.2	43.0	43.0	8.0	-7.1	45.6	45.6	33.6	33.6	114.4	57.9
200-350	4.0	23.0	3.7	47.2	-3.9	13.0	8.0	14.6	-9.8	70.5	70.5	15.6	-13.4	59.8	75.3
250-200	4.0	40.2	-40.2	53.7	38.9	16.9	13.7	14.4	-12.3	7.4	2.6	92.3	92.3	86.8	95.3
250-350	4.0	60.5	8.2	87.9	87.9	45.8	7.8	15.1	-15.1	65.2	65.2	12.6	-12.6	122.0	69.6
350-200	4.0	45.0	-40.2	109.6	109.6	19.4	-0.3	6.8	-3.1	59.8	59.8	19.6	12.9	131.2	64.7
350-250	4.0	45.8	45.8	46.9	-30.8	26.0	26.0	2.9	-2.2	62.3	62.3	8.9	-7.1	81.4	63.4
V-Bar	4.0	41.3	-18.3	44.5	0.7	42.5	-42.5	5.1	4.7	35.3	-35.3	25.8	25.8	79.8	44.5
r		0.471	0.157	-0.374	-0.309	**-0.642**	**-0.763**	-0.442	0.448	**-0.598**	**-0.553**	0.235	-0.005	-0.481	**-0.535**
V [%]		22.2	2.5	14.0	9.6	**41.3**	**58.2**	19.5	20.1	**35.8**	**30.6**	5.5	0.0	23.2	**28.6**

The results of this analysis could be exploited by using the proposed objective metric during the design of a riser to guarantee dynamic performance and a positive user experience.
Of the four best weight configurations previously identified, configuration 200–250 has a dynamic behaviour "*Acceptable*" (compared to the other three configurations rated "*Good*") and is discarded.

9. Subjective metric: Precision

The scoring of 30 arrows per weight configuration is shown in Table 6. The target was a WA – 122 cm, 10-ring target (maximum score 300 points), positioned 50 m away. The archer was from the Archers of the Zoo Lake Club (Advanced archer [16]). Columns three and four report the number of X and 10 and the number of nine scored for each weight configuration (standard WA scoring requirement). The column "Overall Quality" (the average of the three subjective metrics; weight balance, vibrations and dynamic behaviour, refer to Appendix A) has been added for reference.

Table 6 - Scoring by weight configuration

Weight Configuration	Score	Number of X and 10	Number of 9	Overall Quality
Naked	228	3	3	Bad
200-0	247	2	10	Bad
200-250	256	4	12	Good
200-350	260	6	12	Acceptable
250-0	242	5	4	Bad
250-200	262	8	13	Good
250-350	255	2	14	Acceptable
350-0	249	8	7	Acceptable
350-200	249	3	8	Good
350-250	254	3	13	Good
V-Bar	251	4	9	Good

Although this is a standard methodology to compare bow settings or, in this study, weight configurations [28] [29] [30], it has been demonstrated that the differences in score reported in Table 6 are within two standard deviations around the average score, so the results are inconclusive from the relative performance point of view. Assuming an average score of 250 for the eleven weight configurations, Park's theoretical approach [31] could be used to evaluate the archer's skill level index. From Park [32], the mean of the arrows' group width and the standard deviation of the group width can be calculated. A Matlab program was written to simulate the shooting of multiple ends of 30 arrows each. With 100,000 ends simulated (3,000,000 simulated arrows) the average score is 256.35 with a standard deviation of $s = 6.15$. Assuming a level of confidence of 95% (two standard deviations), the possible scores are in the range from 244.05 to 268.65. Every experimental score within these limits is inconclusive from the relative performance point of view. As reported in Table 6, all the recorded scores, except those for the Naked configuration, were within the two-standard deviation range. Unfortunately, with just one end of 30 arrows, it is not possible to assume that the score is the average score for that weight configuration.

The Matlab program was also used to verify how many arrows are necessary to reach stability in the average score. It is suggested that is necessary to shoot at least 30-35 ends per weight configuration (900 to 1,050 arrows) to obtain an average score stable enough to be compared with the average scores from the other weight configurations. It is clear that this approach is ineffective from the comparison of the relative performance point of view. Also, the alternative methodology suggested by Park [32] requires a significant number of arrows to account for the variability in the shooting.
Nevertheless, some comments can be made on this experience. During the tests, the archer was capable of quickly adapting to the shortcoming of the bow and, after some arrows, was shooting efficiently irrespective of the weight configuration. It is suggested that a good shooting technique is capable of overcoming the deficiency of the bow, and this could be the explanation why there is no consensus in the barebow community about the best weight configuration. The archer, instead of going through the time-consuming process of trying all the possible weight configurations and deciding on his/her personal best, would accept the behaviour of the bow and get used to it.
While nothing can be said about the relationship between scores and weight configuration, there is a clear relationship between the physical sensation during the shooting and the weight configuration. It could be argued that, during a long competition, a more balanced bow would provide an advantage to an archer who would be less fatigued at the end of the competition. It was reported by the archer that the configuration 350–250 was “very heavy” and in a long competition could significantly fatigue the archer. Accordingly, this weight configuration was disqualified and so, of the three best weight configurations previously identified, only two are suggested after the precision analysis: 350–200 and 250–200.

10. Discussion

Eleven weight configurations were analysed to determine the best stabilisation configuration in a barebow style bow, as defined by the WA Federation. The problem was analysed using a novel approach that considers objective metrics (measurable quantity), subjective metrics (related to the experience using the sporting equipment) and precision to give a more user-oriented approach to the problem. For the weight configuration analysis, the selected objective metrics were the vibrations of the bow recorded at five different positions along with the bow and the dynamic behaviour of the bow. The subjective metrics were the sensations associated with shooting the bow with different weight configurations. In particular, data were collected about the aiming phase, the vibrations and the dynamic behaviour of the bow in the shooting phase. The scoring associated with the weight configurations was also tested with inconclusive results. Many more shots would be required to relate the shooting precision to the weight configuration. The best weight configuration was decided by considering these three aspects together (metrics correlations).
The best weight configurations are the 350–200 (350 g on the central attachment and 200 g on the lower attachment) and the 250–200 (250 g on the central attachment and 200 g on the lower attachment). These weight configurations guarantee the lowest level of vibration and good dynamic behaviour of the bow on shooting. The archers report a good feeling during the aiming and during the shooting and, with a good archery technique, they allow for a good level of precision on target.
Analysis of the collected data shows that the archer is not sensitive to the duration of the vibration but is sensitive to the amplitude of the vibrations induced by the act of shooting (P2P) and the energy content of the vibration (RMS). The archer is also sensitive to both the high-frequency vibration range (sound) and the low-frequency range (vibration of the riser against the archer’s hand). The lower the vibration, the better the feeling with the double-weight configurations performing constantly better than the single-weight configurations. Among the double-weight configurations, the heaviest of the two weights is better attached to the central attachment and the lightest to the lower attachment.
From the subjective metrics point of view, it was necessary to differentiate between the phases of the shooting to avoid the archer averaging the sensations experienced when using the bow. The archers scored the same weight configuration differently for the different phases of the shooting, generally

preferring a double-weight configuration over a single-weight configuration with the heaviest weight in the central connection point.

11. Conclusion

This work shows that a pure performance-based approach is not enough to capture the complexity of the archer-bow interaction. The methodology developed to solve the proposed problem considers both subjective and objective metrics and the relationship between them. Identifying the objective metrics that correlate with archers' perceptions required considerable effort and drew on some knowledge of human body mechanics and on knowledge in the archery community. When successful, the correlation analysis provides deeper insight into the problem and is extremely effective in understanding what the archer considers to be a good performance of the bow. This knowledge could be used to design better archery equipment from both performance and user experience points of view.

It is suggested that this methodology could be used for every type of sporting equipment and, in particular, for a human-centred improvement of sporting equipment.

Disclaimer

The study was approved by the Human Research Ethics Committee (Non-Medical) of the University of the Witwatersrand to include the use of human participants. The three documents used in this study, the Introduction letter, the Consent form and the Questionnaire, are part of the ethics protocol defined in the Research Ethics document H22/01/25 which was approved by the Human Research Ethics Committee (Non-Medical) of the University of the Witwatersrand on the 28th of January 2022.

All participants in the research signed the Consent form reported in the Research Ethics document H22/01/25 approved by the Human Research Ethics Committee (Non-Medical) of the University of the Witwatersrand on the 28th of January 2022.

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Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

Data

All data used in the paper will be available on request. Please contact the main author by email.

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Appendix A

The following data report the results from the questionnaire administered to the archers of the Archers of the Zoo Lake Club, Johannesburg, South Africa. The weight configurations were scored using a numerical scale ranging from "*very bad*" (numerical score 1) to "*very good*" (numerical score 5). The questionnaire was divided into three questions exploring the archer's sensations associated with the weight configurations, for three different phases of the shooting, namely:

The *weight balance* of the bow during the drawing and aiming phases.

The *vibrations* of the bow during the shooting of the arrow.

The *dynamic behaviour* of the bow after the shooting of the arrow.

The *overall quality* is the average of the three defined metrics.

Weight Balance			
Weight configuration	Results		Evaluation
Naked	2.6	3.0	Acceptable [3]
200-0	2.6	3.0	Acceptable [3]
200-250	3.7	4.0	Good [4]
200-350	3.9	4.0	Good [4]
250-0	2.9	3.0	Acceptable [3]
250-200	3.7	4.0	Good [4]
250-350	3.1	3.0	Acceptable [3]
350-0	3.3	3.0	Acceptable [3]
350-200	3.6	4.0	Good [4]
350-250	3.1	3.0	Acceptable [3]
V-Bar	4.0	4.0	Good [4]

Vibrations			
Weight configuration	Results		Evaluation
Naked	1.4	1.0	Very Bad [1]
200-0	1.4	1.0	Very Bad [1]
200-250	3.6	4.0	Good [4]
200-350	2.9	3.0	Acceptable [3]
250-0	1.7	2.0	Bad [2]
250-200	4.6	5.0	Very Good [5]
250-350	3.3	3.0	Acceptable [3]
350-0	2.3	2.0	Bad [2]
350-200	4.6	5.0	Very Good [5]
350-250	4.1	4.0	Good [4]
V-Bar	4.6	5.0	Very Good [5]

Dynamic Behaviour			
Weight configuration	Results		Evaluation
Naked	1.7	2.0	Bad [2]
200-0	2.0	2.0	Bad [2]
200-250	3.4	3.0	Acceptable [3]
200-350	3.6	4.0	Good [4]
250-0	2.3	2.0	Bad [2]
250-200	3.6	4.0	Good [4]
250-350	3.7	4.0	Good [4]
350-0	2.9	3.0	Acceptable [3]
350-200	3.9	4.0	Good [4]
350-250	3.9	4.0	Good [4]
V-Bar	4.1	4.0	Good [4]

Overall Quality			
Weight configuration	Results		Evaluation
Naked	1.9	2.0	Bad [2]
200-0	2.0	2.0	Bad [2]
200-250	3.6	4.0	Good [4]
200-350	3.4	3.0	Acceptable [3]
250-0	2.3	2.0	Bad [2]
250-200	4.0	4.0	Good [4]
250-350	3.4	3.0	Acceptable [3]
350-0	2.8	3.0	Acceptable [3]
350-200	4.0	4.0	Good [4]
350-250	3.7	4.0	Good [4]
V-Bar	4.2	4.0	Good [4]

Appendix B

The following data are reported in the Global coordinate system. P2P is the root sum of squares of the P2P in the three directions X, Y and Z, as well as RMS is the root sum of squares of the RMS in the three directions X, Y and Z. All data are in g (standard Earth acceleration) but the Time that is in s. r is the Pearson correlation and V is the percentage of the proportion of predictable variability.

Position 1 - Global Coordinate System

Pearson correlation coefficient (r)
Proportion of predictable variability (V=r^2)

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Time [s]
Naked	1	1537.19	1941.99	1535.11	2913.90	127.94	53.41	64.87	153.07	0.5349
200-0	1	1570.45	2034.45	1241.77	2854.34	135.11	59.20	64.80	161.12	0.5361
250-0	2	1509.72	1796.65	1960.51	3057.91	121.96	55.75	68.04	150.37	0.5916
350-0	2	1480.82	1899.79	1583.94	2882.86	121.69	56.84	69.85	151.39	0.5348
200-350	3	1491.34	1979.07	1717.90	3015.29	120.57	57.83	60.11	146.61	0.5843
250-350	3	1481.31	2147.16	1237.94	2887.40	138.19	62.94	64.83	165.10	0.5607
200-250	4	1516.43	2147.86	1221.74	2899.22	141.27	64.88	66.13	168.94	0.4516
350-250	4	1489.04	2078.48	1341.13	2887.21	122.15	59.71	62.76	149.75	0.4743
250-200	5	1447.45	2026.99	1210.04	2769.12	118.06	56.30	58.38	143.23	0.5377
350-200	5	1527.29	2069.06	1211.00	2842.55	122.87	58.77	61.99	149.64	0.4502
V-Bar	5	1526.04	2088.97	1140.50	2827.25	134.48	63.20	47.36	155.96	0.4250

r	-0.412	**0.550**	**-0.547**	-0.480	-0.087	0.469	**-0.625**	-0.180	**-0.628**
v [%]	17.0	**30.3**	**29.9**	23.0	0.8	22.0	**39.1**	3.3	**39.4**

Position 2 - Global Coordinate System

Pearson correlation coefficient (r)
Proportion of predictable variability (V=r^2)

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Time [s]
Naked	1	369.12	223.14	407.58	593.43	30.61	16.82	29.01	45.40	0.1799
200-0	1	348.33	196.39	306.62	503.91	25.86	14.35	21.11	36.34	0.1608
250-0	2	339.95	207.12	356.75	534.54	27.01	13.40	24.96	39.14	0.1738
350-0	2	353.12	201.67	360.85	543.67	24.18	12.13	22.23	35.02	0.1626
200-350	3	331.10	200.15	364.22	531.36	27.87	13.26	24.21	39.23	0.1416
250-350	3	360.22	201.07	303.59	512.21	25.99	14.19	21.00	36.30	0.1384
200-250	4	345.92	194.03	324.34	512.35	25.94	14.17	20.08	35.73	0.1477
350-250	4	336.25	191.86	339.44	514.87	29.45	13.84	24.89	40.97	0.1503
250-200	5	340.87	173.22	301.78	487.10	24.05	11.20	19.97	33.20	0.1498
350-200	5	349.86	190.82	356.19	534.49	25.91	12.74	22.81	36.79	0.1498
V-Bar	5	320.53	159.59	310.00	473.61	24.05	10.96	19.12	32.62	0.1000

r	**-0.546**	**-0.791**	-0.437	**-0.612**	-0.411	**-0.667**	**-0.536**	**-0.539**	**-0.683**
v [%]	**29.8**	**62.6**	19.1	**37.5**	16.9	**44.5**	**28.8**	**29.0**	**46.7**

Position 3 - Global Coordinate System

Pearson correlation coefficient (r)
Proportion of predictable variability (V=r^2)

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Time [s]
Naked	1	394.89	126.39	283.75	502.42	21.81	6.55	17.51	28.73	0.2250
200-0	1	364.87	138.23	287.49	484.65	19.81	6.59	17.98	27.55	0.2884
250-0	2	368.18	135.15	340.30	519.25	20.93	7.58	18.02	28.64	0.2747
350-0	2	394.20	149.42	380.05	567.59	21.61	8.15	18.73	29.74	0.2156
200-350	3	386.85	150.99	433.51	600.32	21.70	7.91	20.63	30.97	0.2432
250-350	3	353.65	129.16	300.81	481.91	19.30	6.75	18.08	27.29	0.1764
200-250	4	367.86	119.12	269.11	471.10	19.61	6.40	17.46	27.02	0.2570
350-250	4	367.95	145.43	414.91	573.31	20.89	7.90	20.02	29.99	0.1973
250-200	5	379.30	149.49	401.35	572.10	21.58	7.99	19.95	30.45	0.2313
350-200	5	342.69	158.84	445.33	583.94	20.79	8.22	20.44	30.29	0.2632
V-Bar	5	296.50	98.78	227.43	386.52	16.42	5.96	12.54	21.50	0.2462

r	**-0.559**	-0.030	0.245	0.025	-0.349	0.162	-0.029	-0.152	-0.113
v [%]	**31.2**	0.1	6.0	0.1	12.2	2.6	0.1	2.3	1.3

Pearson correlation coefficient (r)

Position 4 - Global Coordinate System **Proportion of predictable variability (V=r^2)**

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Time [s]
Naked	1	438.02	275.80	563.85	765.41	25.27	18.45	27.89	41.92	0.1349
200-0	1	472.65	294.91	422.65	699.29	26.08	17.45	19.45	36.92	0.1430
250-0	2	431.49	252.64	772.03	919.80	19.03	14.27	31.32	39.33	0.1435
350-0	2	318.04	216.36	513.81	641.84	16.72	12.46	24.50	32.18	0.1653
200-350	3	539.55	345.98	742.04	980.53	23.73	15.18	30.83	41.77	0.1144
250-350	3	542.85	295.19	464.79	773.21	27.05	17.39	22.10	39.02	0.1147
200-250	4	484.50	292.98	400.20	693.35	26.57	17.59	19.74	37.48	0.1621
350-250	4	323.69	237.46	586.04	710.35	18.57	12.95	26.70	35.01	0.1373
250-200	5	302.45	207.51	482.80	606.33	16.80	12.35	24.82	32.41	0.1374
350-200	5	391.98	228.39	537.30	703.21	20.60	13.34	25.33	35.27	0.1451
V-Bar	5	477.26	268.61	349.21	649.52	25.35	14.79	18.20	34.53	0.1129

r	-0.211	-0.315	-0.292	-0.366	-0.201	-0.496	-0.244	**-0.502**	-0.180
v [%]	4.5	9.9	8.5	13.4	4.0	24.6	5.9	**25.2**	3.2

Pearson correlation coefficient (r)

Position 5 - Global Coordinate System **Proportion of predictable variability (V=r^2)**

Weight Conf.	Quality	P2P X	P2P Y	P2P Z	P2P	RMS X	RMS Y	RMS Z	RMS	Time [s]
Naked	**1**	1575.34	810.66	1168.38	2122.26	120.23	45.72	44.60	136.14	0.4420
200-0	**1**	1664.53	795.81	1177.30	2188.61	120.85	45.73	42.66	136.07	0.4478
250-0	**2**	1623.58	787.46	1268.42	2205.67	110.47	42.46	48.55	127.92	0.5522
350-0	**2**	1610.82	703.10	919.43	1983.55	101.60	40.99	37.18	115.69	0.4683
200-350	**3**	1560.32	773.50	994.88	2005.67	108.88	44.70	42.76	125.23	0.4972
250-350	**3**	1725.30	939.43	1326.59	2370.46	121.21	50.67	42.98	138.22	0.5565
200-250	**4**	1632.64	829.90	1211.67	2195.99	119.52	47.04	42.83	135.39	0.4168
350-250	**4**	1652.36	1099.95	1266.37	2354.54	114.11	55.72	48.67	136.00	0.4798
250-200	**5**	1497.54	763.46	903.84	1908.51	101.02	43.11	35.32	115.38	0.4406
350-200	**5**	1625.71	1068.12	1330.58	2356.74	111.80	52.28	48.89	132.75	0.4835
V-Bar	**5**	1585.72	1197.19	803.52	2143.23	111.12	55.32	34.30	128.79	0.2861

r	-0.260	**0.601**	-0.201	0.093	-0.344	**0.540**	-0.213	-0.179	-0.361
v [%]	6.8	**36.1**	4.0	0.9	11.8	**29.2**	4.5	3.2	13.1

3.5. Critical evaluation of the first paper and the methodology

This first paper was a fundamental step in demonstrating the feasibility of the proposed PhD study. The analysis of the subjective and objective metrics assured a deep understanding of the proposed problem, and the proposed methodology was successful in analysing the problem of the weight distribution on barebow bows from both the archer and the engineering points of view.

In this study, subjective metrics were considered first, then the objective metrics were introduced and the correlations were found (QUAL → QUAN research approach). The use of the Pearson coefficients to study the correlations between metrics was suggested by one of the anonymous reviewers of the paper, while the other reviewer suggested stopping using the objective metric *precision* (score obtained using one of the tested configurations) due to the impractical number of arrows necessary to obtain statistical significance. This conclusion is based on Park's research [4] [5], which correlates the quality of the archer with the number of arrows required for the score to serve as a metric for assessing the effectiveness of a bow configuration, with the necessary statistical significance. It is important to note that the practice of shooting thirty arrows to evaluate the effect of the change in the bow is a common practice, suggested in tuning manuals as the Easton "Arrow tuning and maintenance guide" [3].

The problem of the perceived vibration was another interesting finding. The vibration of the bow was a problem far more complex than anticipated and required the definition of mechanical vibrations, perceived by the archers through the hand-wrist-arm-shoulder system, and the sound of the bow, created by the vibration of the string on release. While mechanical vibrations are limited to 500 Hz accounting for the physiology of the human body, the sound is mainly in the high frequency range. Consequently, it was decided for future studies to differentiate between mechanical vibration and sound and the effect of these metrics on the archers.

In critically evaluating the effectiveness of the methodology, it was decided to try an explanatory sequential mixed methods design for the second paper, or a QUAN → QUAL research approach. With this approach, the researcher first conducts quantitative research, analyses the results, and then builds on the results to explain them in more detail with qualitative research. It was also decided to submit the second paper to the same journal as the first paper: *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*. The reasons for this choice were the quality of the journal[8], the quality of the reviews received for the first paper, and the possibility of submitting papers of substantial length.

[8] https://journals.sagepub.com/home/PIP - Journal Impact Factor: 1.1 / 5-Year Impact Factor: 1.1

Chapter 4

The Effect of the Introduction of Damping in Barebow Style

4.1. Introduction

In March 2022[9], WA rules changed allowing barebow archers to use damping devices on their bows [84]. No scientific publications are available to guide the barebow archer in the decision to introduce damping on the bow, or what type of damping device to choose from. It is important to note that the choice of a modification on the archer's equipment is far from a trivial matter. Changing the bow is a choice that comes after hours of testing, and it is followed by hours of tuning the new bow. In a precision sport like archery, the score in a competition depends directly on familiarity with the sports equipment, and that is only possible after hours of training. In this context, a methodology that is not based on performance only, but that takes into consideration the relationship between the athletes and their sports equipment is fundamental for guiding the choice of changing the bow.

The second study examined the impact of introducing damping in the barebow style and explored how this modification influenced both the objective and subjective metrics related to the analysis of weight distribution on the bow. Building on the first study, this second study allowed a significant refinement in the use of the mixed research methodology in the study of the sport of archery. An explanatory sequential mixed methods design was used in the second paper (QUAN → QUAL approach), first conducting the quantitative part of the research, and then the qualitative part to help explain the first set of results. The number of objective and subjective metrics was increased, as was the number of tested configurations. The vibrations of the bow on shooting were divided into mechanical vibrations, perceived by the archer through the arm supporting the bow, and the sound of the bow on shooting, mainly from the vibration of the string. Eight archers from the Archers of the Zoo Lake Club participated in the study. Of these, five were classified as Intermediate and three as Advanced archers. The classification is based on the guidelines defined in the club [83]: an Intermediate archer is an archer who has completed the six-month Beginner program and has begun competing in regional championships. An Advanced archer is an archer with more than four years of training and participation in national championships. Among this second group of archers, two Intermediate and three Advanced archers had also participated in the previous investigations reported in Chapter 3.

This approach allowed a deep understanding of the archers' perceptions and the relationships between perceptions and the design of the bow components. The concept of the correlation matrix

[9] WA Rulebook, Book 3 Target Archery, Version 2022-03-01 - EN Release 2022-03-02, rule 11.4.6

was introduced and effectively used to gain a deep understanding of the problem. This second study was very successful in correlating the two sets of data (objective and subjective) to understand the physics of the analysed problem, and the relationships between performance, design details and user sensations.

4.2. Methodology

For the second study of this work, an explanatory sequential mixed methods design was used (QUAN → QUAL approach), first conducting the quantitative part of the research, and then the qualitative part to gain a better understanding of the quantitative set of results [1] [2].

The quantitative (QUAN) research tool

The objective metrics considered in the study were the vibration of the bow evaluated at five positions along the bow, divided into mechanical vibrations, perceived by the archer through the arm supporting the bow, and the sound of the bow on shooting, mainly from the vibration of the string. Fifteen single-weight and thirty-six double-weight configurations were tested. All damped weights were created by the author except for the commercially available Gray Dampering damped weights [85]. At the time of this study, the only way to introduce damping in the barebow weight system was to buy rubber washers for plumbing and decouple the weight from the riser with a layer of damping material. Considering the single-weight configuration, Configuration A is the commercially available GasPro weight [86] used in the first study, here analysed as the reference, undamped configuration. Configuration B was created by layering two Bonded EVA Washers [87] (commercially available in every hardware store), with a 3.3 mm silicon washer [87] (commercially available in every hardware store). Configuration C was a vibration damper used for damping washing machines. Unfortunately, only one damper was available because the screw, a 5/16-24 UNF, is no longer a standard for American washing machines. Configuration D was created by stacking alternatively disks of brass, 50 g each, and 3.3 mm silicon rubber washers until the required total weight was obtained. Configuration E was the commercially available Dampering, from Gray Archery [85]. It comprises an external ring of stainless steel of 51.5 g (part 'A', Figure 15); an internal connection part of 15.5 g, also in stainless steel (part 'B', Figure 15); and an intermediate silicon rubber ring of 3 g (part 'C', Figure 15), for a total weight of 70 g. The thirty-six double-weight configurations were obtained by combining the single-weight configurations.

The data were collected using a single archer (the author) to shoot all tested configurations, with three shots taken per configuration. The mechanical vibrations of the bow were measured in the Archery Laboratory, North West Engineering Building, University of the Witwatersrand, Johannesburg. The

sound of the bow on shooting was recorded outdoors, at the Archers of the Zoo Lake Club range (Johannesburg, South Africa), early in the morning to avoid other sources of sound.

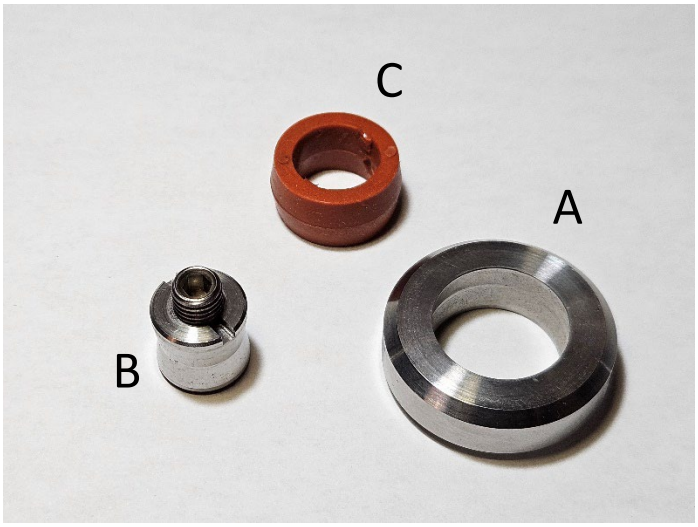


Figure 15 - Dampering from Gray Archery

The qualitative (QUAL) research tool

Four subjective metrics were chosen for the research: the level of mechanical vibration of the bow, the sound of the bow on release for both intensity and pitch of the sound, and the overall quality of the tested configurations. The decision about the subjective metrics was based on the experience accumulated during the first study. The sound of the bow on release was introduced to evaluate how sensitive the archer is to the sound of the bow, and if the sound of the bow is a determining factor in evaluating the quality of the design. Due to limited testing time, not all fifty-one weight configurations could be tested. Five good-performing weight configurations were selected (one single-weight (350-0) and four double-weight configurations (200-250, 250-200, 350-200 and 350-250). The decision was based on the results of the previous study. Eight archers from Archers of the Zoo Lake Club participated in the study. The archers were selected using the same criteria as in the first study, employing both purposive and convenience/opportunistic sampling methods. Unfortunately, a group of eight archers is not enough to reach saturation. The eight archers were the only intermediate or advanced-level archers available at the time of testing. To better differentiate between vibration perception and sound perception, the archers were divided into pairs: one archer shooting the bow ('archer') and the other archer listening to the sound of the bow ('observer'). The 'archer' wore earplugs to reduce the sound of the bow on shooting and was requested to evaluate the vibration level of the bow and the quality of the weight configuration. The 'observer' was requested to evaluate the sound of the bow both in intensity and pitch. After the conclusion of the tests, the pair swapped roles and the tests were run again. A questionnaire was administered after the test of each

configuration to collect the subjective metrics. Like the questionnaire in the first study, this questionnaire was also tested and refined by the three coaches of the Archers of the Zoo Lake Club. The questionnaire is available in Appendix E.

The same confounding variables [1] [2] [11] [12] identified in the first investigation were considered and controlled, the only difference being the potential bias of the researcher. As a recurve archer with years of experience experimenting with damping on the stabilisation systems, the author personally believes in the advantages of introducing damping on the bow. However, the author did not have preconceived notions regarding which damping solution was optimal for a barebow design, and therefore, all results are believed to be unbiased.

4.3. Contribution of the author to the second paper and contribution to knowledge

The idea of evaluating the effect of the damping on the bow was already discussed during the writing of the first paper. Judging the methodology used in the first paper already complex enough, the authors decided to postpone the study of the damping effects on the bow. However, after the publication of the first paper, the effect of damping was considered a good subject for refining the use of the mixed research methodology. The author defined the objective and subjective metrics for this new study and created the questionnaire to collect the subjective metrics. The questionnaire is available in Appendix E. The tests (objective metrics) were executed from March to August 2023 by the author, while the questionnaire was administered to the archers of the Archers of Zoo Lake Club in August 2023, also by the author. The data analysis was a challenging task with the analysis of thirteen metrics and seventy-eight correlations. As for the first paper, the interactions with the two supervisors Profs. Loveday and Reid were fundamental to refine the methodological approach to the problem and to understand the physics behind the collected data. The writing of the paper was completed by the author in October 2023 and the paper was published in a second journal article with the title 'Objective and subjective measurements of the influence of dampers on the shooting experience of barebow archers'. The paper was published in Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology on the 3rd of February 2024 (online publication).

Regarding the paper's contribution to knowledge, this second study demonstrates the potential of the mixed research methodology in understanding complex problems involving engineering measurements, design and athletes' perceptions of sports equipment. This methodology was again successful in analysing a complex problem and suggesting a solution based on athletes' preferences and scientific measurement of performance.

The paper is available at the following link:

https://journals.sagepub.com/doi/10.1177/17543371231213420?icid=int.sj-full-text.citing-articles.1

4.4. Second journal paper: Objective and subjective measurements of the influence of dampers on the shooting experience of barebow archers

The following paper is in the "accepted manuscript" version, maintaining its original structure as submitted for publication. It is presented with single-line spacing to distinguish it from the rest of the thesis. The first page of the published version of the paper is available in Appendix A. The paper is reproduced under the terms of Sage's Author Archiving and Re-Use Guidelines. Please see Appendix G for details.

Title
Objective and subjective measurements of the influence of dampers on the shooting experience of barebow archers

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Abstract
The barebow archery shooting style previously limited the stabilisation system to weights connected to the riser, which is the central part of the bow, but recently the use of damping devices has been allowed. No scientific study is available to evaluate the effect of damping on the archers' shooting experience. A human-centred methodology was developed to address this problem. Objective metrics (measurable quantities) and subjective metrics (archers' sensations using the equipment) were defined. These metrics were correlated to obtain a deeper understanding of the problem.
Fifty-one weight configurations were tested for mechanical vibrations and sound of the bow on shooting. The mechanical vibration was measured at five positions on the bow. Fifteen configurations were selected and tested by eight archers to evaluate the subjective metrics. The results show that dedicated vibration-damping devices are capable of significantly reducing the mechanical vibrations and the intensity and pitch of the sound of the bow on shooting. A strong correlation exists between reduced vibrations, lower intensity and pitch of the sound of the bow and the quality of the shooting experience.
The methodology used in this work was successful in fostering an understanding of the relationship between objective and subjective metrics on shooting. The results of this analysis could be used to improve existing designs or create new products for archery.

Keywords
Archery, barebow, barebow weight configurations, damping, subjective metrics, objective metrics, bow vibrations, bow sound, correlation, archer's experience, World Archery.

List of Notation

CoG	Centre of gravity
DAQ	Data acquisition system
MSV	Mean Squared value
P2P	Maximum to Minimum Difference
RMS	Root Mean Squared value
WA	World Archery Federation
Max SPL	Maximum Sound Pressure Level
L_{eq}	Equivalent Continuous Sound Level
SPL	Sound Pressure Level
r	Pearson correlation coefficient
V	Coefficient of Determination

Introduction

World Archery (WA) is the international federation responsible for the Olympic and Paralympic sport of archery. WA also organises international events, including a world championship [1], for the three archery styles: compound, recurve, and barebow. Recurve and barebow archers use the same type of bow, but in the barebow style use of the sight and the clicker are not allowed and the V-Bar stabilisation system of the recurve style is limited to simple weights attached to the riser (the central, rigid part of the bow) [2].

The main functions of a stabilising system (weights added to the bow to stabilise its motion during shooting) are the control of the movement of the bow during the aiming phase, the control of vibrations [3], and control of the dynamic action of the bow on string release [4] [5].

The dynamic behaviour of the bow on release is related to the weight configuration in comparison to the position of the centre of gravity (CoG) of the bow. A Cartesian coordinate system is defined as centred on the pressure button [6] (Figure 1). The X axis follows the direction of the arrow, parallel to the ground. The Y axis lies in the plane of the bow (the plane created by the string and the middle section of the limbs), upward. The Z axis is perpendicular to the XY plane and on the right (as seen by the archer).

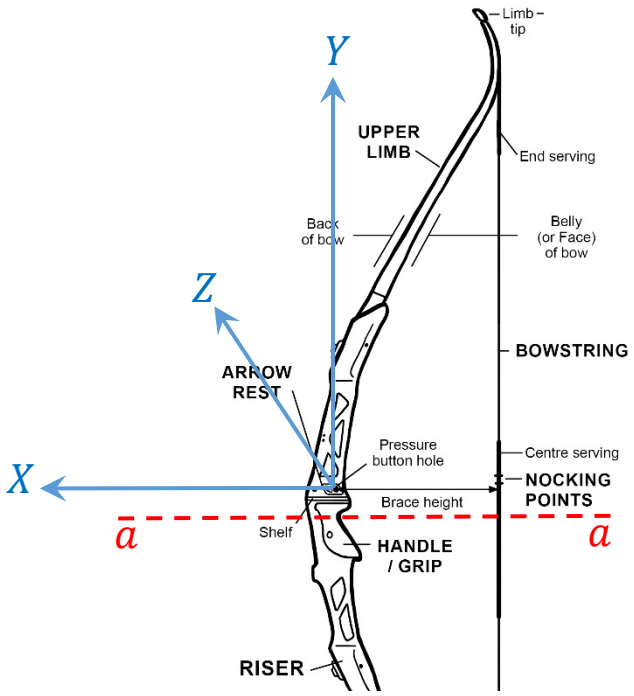


Figure 1 – Global coordinate system [7]

Without stabilisation, the CoG of the bow is positioned at the same height as the handle (line $a-a$), behind the handle on the XY plane. On release, the bow rotates around the $+Z$ axis (positive rotational direction according to the right-hand rule) [8]. The stabilisation system is designed to move the CoG ahead of the handle and along the $-Y$ direction. On release, the stabilised bow initially moves in the X direction, then the riser is caught by the finger sling (a piece of string that connects the index and the thumb of the archer) and rotates around the $-Z$ axis [8]. This rotation is the desired dynamic behaviour of the bow because the movement in the X direction does not affect the launching of the arrow and the $-Z$ axis rotation moves the upper limb away from the archer's face. In the barebow style, the stabilisation system was previously limited to weight(s) that may be added to the riser [2] at the centre attachment point (Figure 2, 'A') and at the lower attachment point (Figure 2, 'B'). The upper attachment point (Figure 2, 'C') is never used because the CoG of the bow must be moved in the X and $-Y$ directions [8]. The stabilisation system allowed for in the barebow style ensures the

displacement of the bow in the $-Y$ direction and its rotation around the $+X$ axis, but it has little to no effect on rotations around the $+Y$ axis.

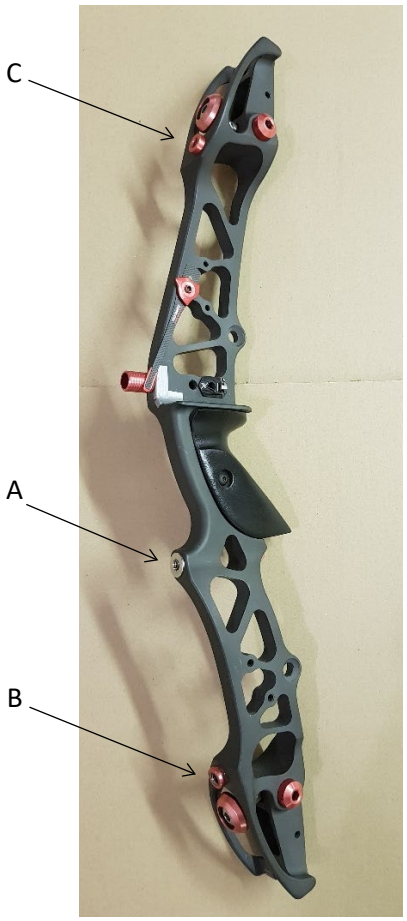


Figure 2 - Weight attachment points A, B and C

On the 7th of February 2020, WA introduced a new rule regarding weights and dampeners on the barebow style (Book 3, Version 2020-02-07):

11.4.6 No stabilisers are permitted.

> *11.4.6.1 Vibration dampeners are permitted. They may be installed in the riser by the manufacturer, or by attaching aftermarket dampeners directly to the riser or to weight(s). Any combination of weight(s) and vibration dampener(s) must pass through a ring with an inside diameter of 12.2 cm (+/- 0.5mm) without having to flex vibration dampeners to fit through the 12.2 cm ring. […] Weight(s) and dampener(s) may be added below and above the riser's grip, but must not aid the athlete in aiming or ranging in any way* [2].

Rule 11.4.6 opened the possibility for barebow archers to use damping devices on their bows together with the previously permitted weights. As found by Pietra and al. [9], there is an inverse correlation between the amplitude of the vibrations recorded on the bow and the comfort of shooting. It was expected by the authors that barebow archers would have adopted damping devices on their bow to take full advantage of the new rule. Nevertheless, of the thirty-two barebow finalists in the 2022 Lancaster Archery Classic for men [10] and women [11], and the 2023 Lancaster Archery Classic for men [12] and women [13], not a single archer introduced any damping in the bow apart from limb dampers.

In this paper, the effect of damping the weights attached to the riser is studied from both an objective point of view (measurement) and a subjective point of view (physical sensation while shooting) to understand what effects damping has on the behaviour of the bow, on the different phases of the shooting sequence and, ultimately, on the archer's shooting experience.

Methods

In the following work, a two-fold methodology is developed to evaluate the effects of the introduction of damping on the barebow style. Initially, an engineering approach is developed which considers the effects of weight distribution and damping on the level of vibration in the bow and the sound of the bow. Subsequently, an archer-centred approach is developed to evaluate the impact of damping on the shooting sequence and the archers' shooting experience. This two-fold approach is deemed to be necessary when trying to understand problems that involve human experiences [9]. The measurement of the effect of damping on the bow is useful from the engineering point of view (design of new equipment, optimisation) but does not describe the archer's experience. Without considering the human aspect of the problem, the solution will be an interesting engineering exercise of limited value for the archery community.

The engineering approach was developed by defining objective metrics to be measured during the shooting of the arrow. The weight distribution on the riser affects the behaviour of the bow in three different ways: weight balance (affecting the aiming phase), vibrations (due to the release of the arrow) and dynamic behaviour (how the bow behaves after the release of the arrow) [9]. Adding dampers to the weight affects principally the vibrations of the bow which can be further divided into mechanical vibrations and the sound of the bow on shooting. Consequently, the mechanical vibration and the sound of the bow on release were defined as objective metrics. The objective metric *precision* on target was not selected because the dampers do not affect the aiming phase and the impractical number of shots necessary to have statistical significance [14] [15].

Various weight configurations and levels of damping were analysed to understand the effect of damping on the vibration of the bow. The archer-centred approach was developed by administering a questionnaire to archers asking about their experience using the bow under a selection of weight configurations and damping levels previously studied in the scientific approach. The questionnaire asked about the physical sensation of shooting with a particular configuration of the stabilisation system. For this particular study, the archers were asked to evaluate the level of mechanical vibration of the bow, the sound of the bow on release for both intensity and pitch of the sound, and to evaluate the overall quality of the tested configuration (subjective metrics). The study of the correlation between objective and subjective metrics gives insight into this problem seeking a relationship between what is measured and what is perceived by the archers.

Experimental Set-Up

The riser used in the experiments was the Gray AIX 2019 [16], which is considered within the South African barebow community to be one of the best risers for this style [17]. The limbs were the Win&Win Limbs Wiawis NS Wood (long version, 32 lb nominal poundage) [18]. Five different configurations, each with three different masses, were analysed for the single-weight configuration problem. In all cases, the weights were attached only to the centre attachment (Figure 2, 'A'). Configuration A used a Gas Pro Barebow Weight [19] and served as a baseline. Configuration B added a 3.3 mm rubber washer enclosed by two steel washers and Configuration C added a vibration damper to the Gas Pro weight. Configuration D was created with 50 g brass discs separated by 3.3 mm rubber washers. Configuration E was created by stacking the Gray Dampering [16]. These configurations are presented in Table 1. The vibration damper available for testing is not compliant with the rules for the barebow style (WA rule 11.4.6.1, 12.2 cm ring rule [2]) when connected to the Gas Pro weights (Configurations C). Configurations D and E in the 350-0 weight configurations are also not compliant. All these configurations were tested as technology demonstrators to compare the results with the baseline configurations. The *real weight* referred to in Table 1 measures the effective weight attached to the riser.

Table 1 - Single Weight configurations

Configuration 200 - 0

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E
					
Real weight	213.12 g	219.76 g	274.14 g	229.5 g	210.47 g

Configuration 250 - 0

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E
					
Real weight	264.27 g	270.91 g	325.29 g	280.41 g	266.36 g

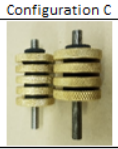
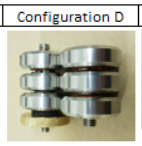
Configuration 350 - 0

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E
					
Real weight	364.4 g	371.12 g	425.45 g	382.62 g	350.24 g

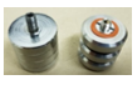
Six different damper configurations, each having six different combinations of weights on the central and lower attachments (Figure 2, 'A' and 'B', respectively) were analysed for the double-weight configuration problem.

Table 2 - Double Weight configurations

Configuration 200 - 250

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E	Configuration F
						
Nominal Weights	Central 200g Lower 250g	Central 200g Lower 250g	Central 200g Lower 250g	Central 200g Lower 250g	Central 200g Lower 250g (D)	Central 200g (D) Lower 250g
Real weight	477.09 g	490.46 g	509.92 g	476.59 g	479.29 g	474.43 g

Configuration 200 - 350

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E	Configuration F
						
Nominal Weights	Central 200g Lower 350g	Central 200g Lower 350g	Central 200g Lower 350g	Central 200g Lower 350g	Central 200g Lower 350g (D)	Central 200g (D) Lower 350g
Real weight	577.23 g	590.59 g	620 g	559.91 g	563.07 g	574.07 g

Configuration 250 - 200

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E	Configuration F
						
Nominal Weights	Central 250g Lower 200g	Central 250g Lower 200g	Central 250g Lower 200g	Central 250g Lower 200g	Central 250g Lower 200g (D)	Central 250g (D) Lower 200g
Real weight	477.09 g	490.46 g	509.92 g	476.59 g	474.41 g	479.26 g

Configuration 250 - 350

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E	Configuration F
						
Nominal Weights	Central 250g Lower 350g	Central 250g Lower 350g	Central 250g Lower 350g	Central 250g Lower 350g	Central 250g Lower 350g (D)	Central 250g (D) Lower 350g
Real weight	640 g	653.37 g	660 g	620 g	620 g	640 g

Configuration 350 - 200

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E	Configuration F
						
Nominal Weights	Central 350g Lower 200g	Central 350g Lower 200g	Central 350g Lower 200g	Central 350g Lower 200g	Central 350g Lower 200g (D)	Central 350g (D) Lower 200g
Real weight	577.23 g	590.59 g	620 g	559.91 g	574.07 g	563.07 g

Configuration 350 - 250

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E	Configuration F
						
Nominal Weights	Central 350g Lower 250g	Central 350g Lower 250g	Central 350g Lower 250g	Central 350g Lower 250g	Central 350g Lower 250g (D)	Central 350g (D) Lower 250g
Real weight	640 g	653.37 g	660 g	620 g	640 g	620 g

The first number in the configuration name refers to the nominal weight attached to the centre attachment, and the second number refers to the nominal weight attached to the lower attachment (Figure 2). Configuration A used two Gas Pro Barebow Weights [19], which are weights that do not include damping, and was used as a baseline to compare the effects of damping. Configurations B to F had different damping elements included. Configuration B had a 3.3 mm rubber washer enclosed by two steel washers added onto each weight. Configuration C was created by stacking 50 g brass discs between 3.3 mm rubber washers. Configuration D was created by stacking the Gray Dampering [16]. Configurations E and F each used a Gas Pro weight and Gray Dampering weights: the (D) in Configurations E and F indicates which of the two weights was the damped one. These configurations are documented in Table 2.

The maximum number of Gray Damperings that can be stacked on the Gray riser according to WA rules (12.2 cm ring rule [2]), is four on the central attachment and three on the lower attachment, so the five Damperings necessary for the 350 g weight exceeds the maximum dimensions allowed by WA rules. The same problem arises with the 350 g weight created by stacking 50 g brass discs. Nevertheless, these configurations were tested for comparison with the undamped baseline configuration.

The *nominal weight* reported for the thirty-six double-weight configurations recorded in Table 2, refers to the mass of the attached weight while the *real weight* measures the sum of the effective weights attached to the riser.

Of all the proposed configurations, only the Gray Dampering is a commercially available solution designed for archery. Three years after the first publication of the 11.4.6 WA rule, the major archery brands do not offer any damped weights for the barebow style.

The arrows were shot using the standard hooking for the barebow style: the three-fingers-under-the-arrow style. To avoid inconsistency between the tests, gap-shooting was preferred as the aiming style compared to string-walking [20]. In the gap-shooting aiming style, the archer places the point of the arrow on a different area of the target to compensate for the shooting distance. In the string-walking

aiming style, the archer places the point of the arrow on the centre of the target and increases the distance between the arrow and the index finger to compensate for the shooting distance. This latter aiming system was not utilised because it could change the tension of the lower limb (the limbs are the flexible part of the bow) and its mechanical vibrations. The bow was set up for the barebow style and tuned using the procedure described by Kaminsky [21].

Objective metric: mechanical vibrations of the bow on shooting

As reported by Pietra et al. [9], archers perceive the vibration of the bow in two different ways: airborne sound and mechanical vibration of the riser. The sound is assumed to originate from the vibrating part of the bow, mainly the string and the limbs. The mechanical vibration of the riser is perceived through the archer's fingers, wrist, arm, and shoulder and only a low-frequency vibration lower than 500 Hz can be perceived. Accordingly, the researchers for this paper decided to measure the mechanical vibration of the bow independently from the sound of the bow.

The vibrations associated with the shooting phase were recorded using a triaxial accelerometer from PCB Piezotronics [22] and a data acquisition (DAQ) system from National Instruments [23]. The nominal signal sampling rate was 12,000 Hz and the signal was recorded over a period of 15 s.

The three acceleration signals were captured at five different positions on the bow (Figure 3). The test was repeated three times for each position of the accelerometer and every weight configuration defined in Tables 1 and 2. Position 1 of the accelerometer was defined on the upper limb, at a distance of 350 mm from its attachment bolt. Position 2 was defined on the riser, 40 mm from the top of the riser. Position 3 was defined on the riser, next to the second hole of the pressure button. This position is close to the archer's hand position on the bow. Position 4 is symmetric to Position 2 on the lower section of the riser. Position 5 is symmetric to Position 1 on the lower limb.

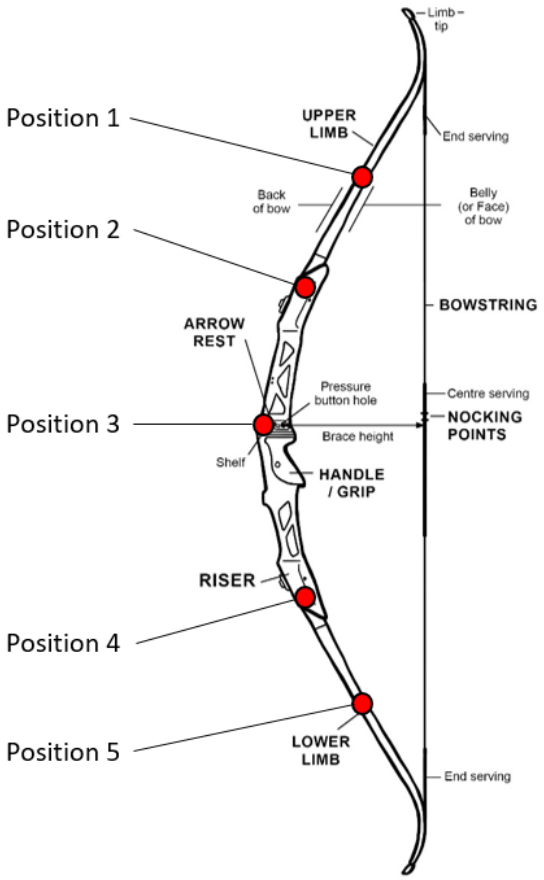


Figure 3 - Positioning of the triaxial accelerometer on the bow. Definition of the five measuring positions

The vibration measurement procedure and signal processing methods developed in prior work of the authors [9] were used. The mechanical vibration data were filtered with a lowpass filter at 500 Hz [24] [25]. The following data statistics were calculated: the *Maximum to Minimum Difference* (P2P), which is a measure of the maximum amplitude of the signals, in units of *g* (Earth's standard gravity constant). The *Root Mean Squared value* (RMS) of the signal, which is the square root of the *Mean Squared value* (MSV) of the signal, also in units of *g*. The MSV is defined as the average squared value of the signal over the time interval. The *Damage* [26] evaluates the intensity of the vibrations acting on the human arm. The Damage was calculated by counting the peaks in the filtered data with the Rainflow method and multiplying the sorted bin edges by the number of occurrences. The *Decay Time* records the time necessary for the signal to reduce from the maximum amplitude to 5% of the maximum amplitude, measured in seconds.

P2P, RMS, Damage, and Decay Time data were averaged across the three shots. Because the five measuring positions have different local coordinate systems, the data were rotated into the global coordinate system defined in Figure 1.

The following data are for Position 3 which is the closest to the archer's hand (Table 3). All data, for the other positions, are reported in Appendix A.

Table 3 – Mechanical vibration, Position 3, data filtered with a lowpass filter at 500 Hz

Configuration 200 - 0

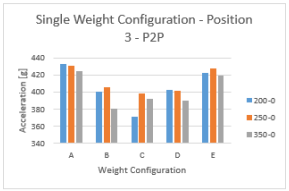
	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P [g]	433.00	400.00	371.38	402.54	422.70
RMS [g]	30.97	25.40	21.83	25.52	29.63
Damage	6505	4994	3794	4821	6368
Decay Time [s]	0.148	0.088	0.117	0.104	0.127

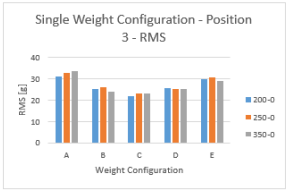
Configuration 250 - 0

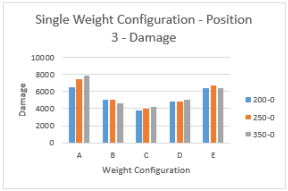
	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P [g]	430.18	405.57	397.97	400.85	427.29
RMS [g]	32.73	26.04	23.10	25.34	30.76
Damage	7474	5013	3974	4811	6701
Decay Time [s]	0.128	0.111	0.096	0.097	0.116

Configuration 350 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P [g]	424.63	380.33	391.80	389.77	419.43
RMS [g]	33.59	24.11	23.00	25.38	29.16
Damage	7820	4653	4202	5003	6432
Decay Time [s]	0.143	0.108	0.104	0.102	0.117









Configuration 200 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P [g]	452.63	384.34	415.53	315.06	339.73	418.11
RMS [g]	29.31	21.89	22.99	19.62	20.45	26.61
Damage	5855	3735	4033	3441	3626	4856
Decay Time [s]	0.116	0.113	0.078	0.151	0.139	0.125

Configuration 200 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P [g]	443.81	401.89	388.93	308.24	339.84	417.28
RMS [g]	28.51	22.59	22.63	19.79	21.23	27.45
Damage	5335	3901	4102	3588	3878	5057
Decay Time [s]	0.099	0.113	0.117	0.118	0.198	0.125

Configuration 250 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P [g]	423.78	407.13	431.99	384.45	425.51	469.56
RMS [g]	26.57	22.24	23.41	25.37	26.96	29.26
Damage	5232	3610	4098	4640	5372	5610
Decay Time [s]	0.175	0.093	0.177	0.102	0.107	0.098

Configuration 250 - 350

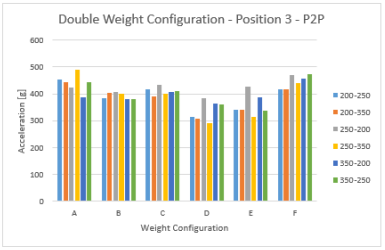
	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P [g]	488.57	400.60	399.97	289.98	314.82	441.19
RMS [g]	32.43	22.42	22.92	18.94	20.01	28.26
Damage	6739	3767	4121	3300	3862	5157
Decay Time [s]	0.118	0.117	0.117	0.089	0.120	0.095

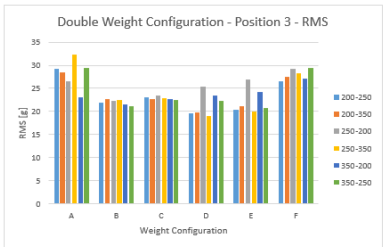
Configuration 350 - 200

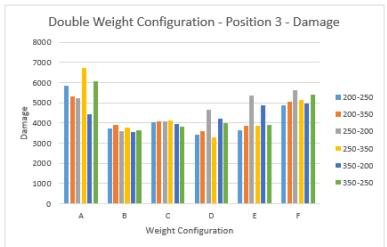
	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P [g]	388.47	381.65	406.82	362.08	387.74	454.99
RMS [g]	23.00	21.43	22.68	23.42	24.29	27.18
Damage	4428	3571	3961	4198	4857	4985
Decay Time [s]	0.134	0.092	0.077	0.097	0.163	0.071

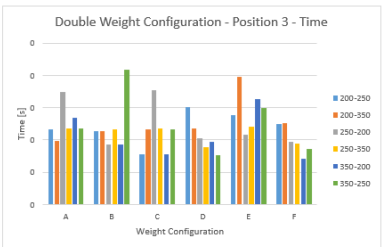
Configuration 350 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P [g]	444.40	381.21	410.28	360.62	337.99	473.47
RMS [g]	29.42	21.19	22.58	22.26	20.69	29.47
Damage	6050	3625	3826	3984	3896	5399
Decay Time [s]	0.117	0.208	0.117	0.076	0.150	0.086









The data analysis for the single-weight configurations shows that every damped configuration performs better than the undamped baseline configuration (Configuration A) from the mechanical vibration point of view. The best-performing configuration is Configuration C (vibration damper). Although this technology demonstrator is not compliant with WA rules (12.2 cm ring rule), this configuration indicates the kind of solution required for barebow archers to minimise the mechanical

vibration of the bow. For the double-weight configurations, Configurations B, C, D and E have better performance than Configuration A (undamped weights), with Configuration D (Gray Dampering) the best-performing of the solutions. Configuration F (damped weight on the centre attachment), performs similarly to Configuration A, and is significantly worse than Configuration E (damped weight on the lower attachment). The data for the Decay Time do not follow the same trend as for the other measures.

Objective metric: the noise of the bow on shooting

The sound emitted by the bow on shooting was recorded with the GRAS 40PH-10 CCP Free-field Array Microphone [27] and a data acquisition (DAQ) system from National Instruments [23]. Three shots were recorded for each weight configuration and the recordings were trimmed to 0.5 s around the release (event duration). The measurements were recorded outdoors at the Archers of the Zoo Lake Club range (Johannesburg, South Africa) early in the morning to avoid other sources of sound. The three shots for the 200 – 0 weight version of Configuration A are shown in Figure 4. As reported in the figure, the three measurements of the sound of the bow on shooting are fairly repeatable and representative of each weight configuration.

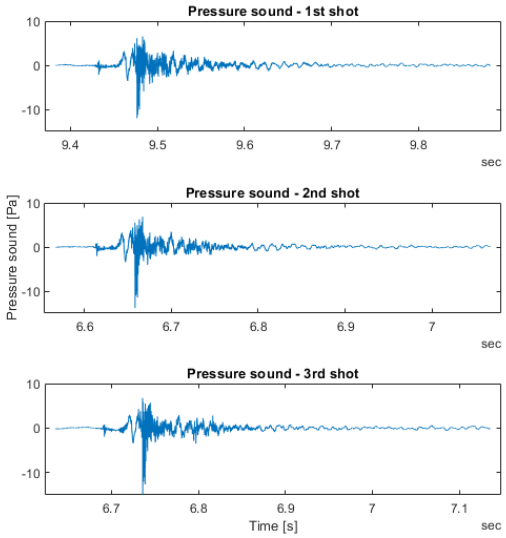


Figure 4 - The three shots for the 200-0, Configuration A. 0.5 s recording

The sound signal was filtered with an A-Weighted filter to account for the different sensitivity of the microphone compared to the human ear. The A-Weighted filter is a bandpass filter designed to simulate the perceived loudness of low-level tones to a human listener. The filter progressively de-emphasizes frequencies below 500 Hz [28] as illustrated in Figure 5. The filter characteristics roughly represent the inverse of the hearing level curve with 30 dB at 1 kHz. The A-Weighting function is standardized in EN 60651 [29]. The effect of the A-Weighting filter on the sound signal is shown in Figure 6 for the time domain, and in Figure 7 for the frequency domain.

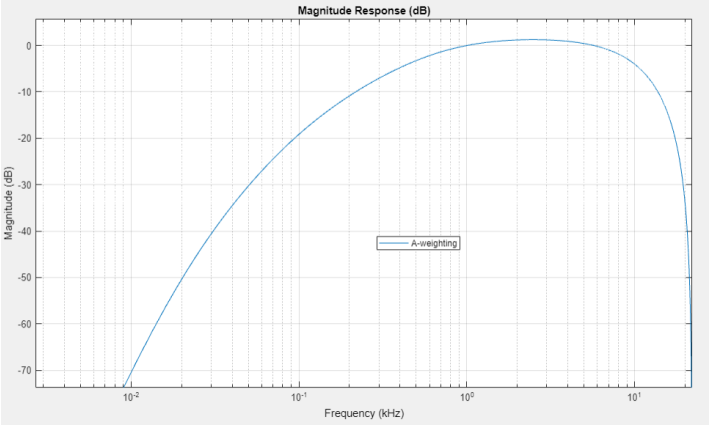


Figure 5 - A-weighting filter [28]

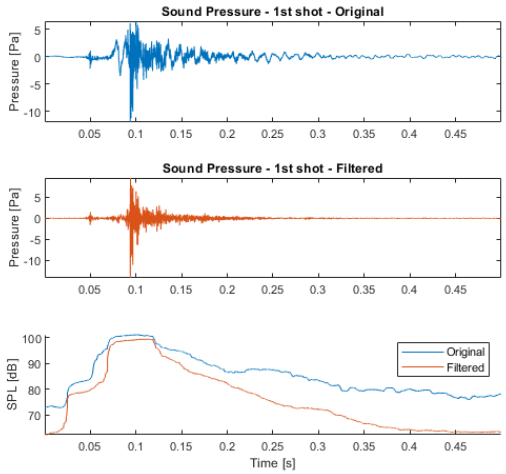


Figure 6 - 200-0, Configuration A - 1st shot signal filtered with an A-Weighted filter. Time domain

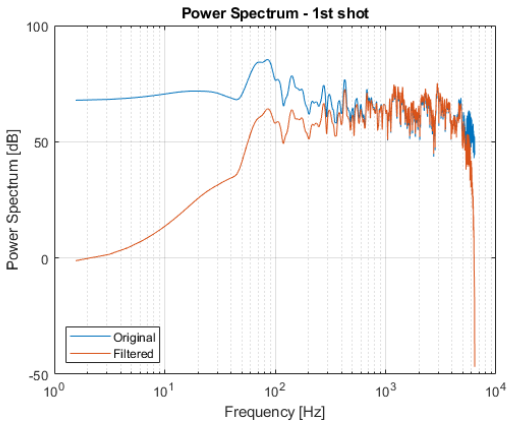


Figure 7 - 200-0, Configuration A - 1st shot signal filtered with an A-Weighted filter. Frequency domain

The *Maximum Sound Pressure Level* (Max SPL) and the *Equivalent Continuous Sound Level* (L_{eq}) were subsequently calculated. The SPL was calculated using the *Sound Pressure Level Calculator* by C. Greene [30], and considering a reference time equal to 0.5 s. The L_{eq} value was calculated using the equation provided in the MathWorks documentation [28]:

$$L_{eq} = 10 \cdot \log_{10}\left[\frac{\left(\frac{1}{T}\right)\int_{t_1}^{t_2} y^2 dt}{p_0^2}\right] = 20 \cdot \log_{10}\left[\frac{RMS(y)}{p_0}\right] \quad (1)$$

where y is the output of the frequency-weighted filter, p_0 is the reference sound pressure ($p_0 = 20 \cdot 10^{-6}\ N/m^2$) and RMS is the root mean squared value of the filtered signal [28]. The data for the single-weight configurations are reported in Table 4, while the data for the double-weight configurations are reported in Table 5.

Data analysis shows that Configuration C is the quietest amongst the single-weight configurations with a reduction in Max SPL from a minimum of 5.9 dB to a maximum of 6.8 dB compared to Configuration A; followed by Configuration E with a reduction in Max SPL from a minimum of 2.7 dB to a maximum of 5.8 dB compared to Configuration A. For double-weight configurations, the quietest is Configuration D with a reduction in Max SPL from a minimum of 1.4 dB to a maximum of 5.9 dB compared to Configuration A.

Regarding the frequency content of the filtered sound for the single-weight configurations, Configurations C and E have a significant reduction in SPL mainly for frequencies greater than 1,000

Hz compared to Configuration A. Figure 8 reports the power spectrum of three single-weight configurations, namely A, C, and E, for the 250-0 weight configuration. The damped single-weight configurations C and E are seen to significantly reduce the SPL, especially at higher frequencies. Figure 9 reports the power spectrum of four double-weight configurations, namely A, D, E, and F, for the 250-200 weight configuration. It can be also seen that for the double-weight configurations, Configurations D, E, and F have a significant reduction in SPL for frequencies greater than 700 Hz compared to Configuration A. The double-weight configuration without damping (Configuration A) had higher SPL below 1,500 Hz and lower SPL above 1,500 Hz compared to the single-weight configuration without damping. The addition of the second weight have significantly reduced the higher-frequency sound radiation. The power spectrum of all configurations is reported in Appendix B.

Table 4 – Sound of the bow, data filtered with an A-Weighted filter, single-weight configurations

Configuration 200 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
Max SPL [dB]	99.1	97.0	93.0	97.0	95.5
Leq [dB]	89.5	87.5	84.0	87.6	86.4

Configuration 250 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
Max SPL [dB]	98.3	96.6	92.4	97.2	95.6
Leq [dB]	88.9	87.3	83.2	87.8	86.5

Configuration 350 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
Max SPL [dB]	99.3	97.1	92.6	97.5	93.5
Leq [dB]	89.7	87.7	83.7	88.1	84.6

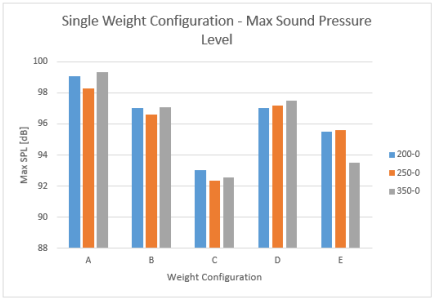




Table 5 – Sound of the bow, data filtered with an A-Weighted filter, double-weight configurations

Configuration 200 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
Max SPL [dB]	93.9	93.4	95.4	91.0	91.6	92.3
Leq [dB]	86.6	84.3	86.0	82.5	83.2	84.2

Configuration 250 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
Max SPL [dB]	96.5	92.6	94.6	91.0	92.5	93.5
Leq [dB]	88.9	83.7	85.4	83.0	84.3	84.7

Configuration 350 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
Max SPL [dB]	95.1	95.7	94.5	92.0	94.5	93.6
Leq [dB]	86.3	86.5	85.7	83.8	85.7	85.3

Configuration 200 - 350

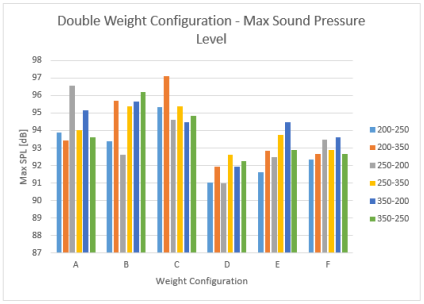
	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
Max SPL [dB]	93.4	95.7	97.1	91.9	92.8	92.7
Leq [dB]	85.1	86.5	87.6	84.2	84.7	84.4

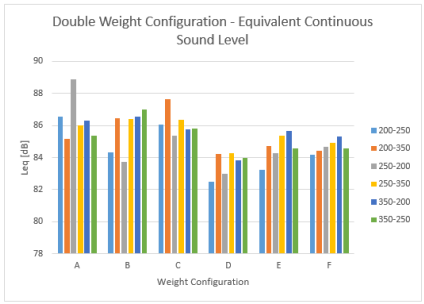
Configuration 250 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
Max SPL [dB]	94.0	95.4	95.4	92.6	93.8	92.9
Leq [dB]	86.0	86.4	86.4	84.3	85.3	84.9

Configuration 350 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
Max SPL [dB]	93.6	96.2	94.8	92.3	92.9	92.7
Leq [dB]	85.4	87.0	85.8	84.0	84.6	84.6





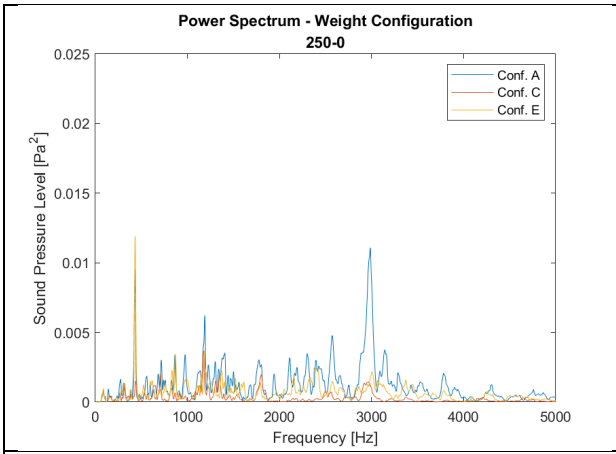


Figure 8 - 250-0 – Power Spectrum of the filtered sound of Configurations A, C, and E

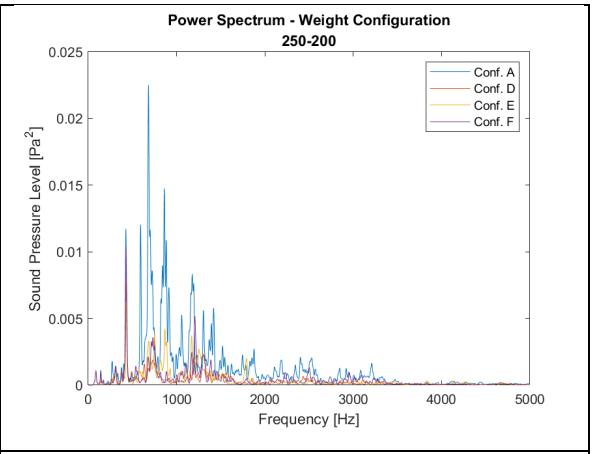


Figure 9 - 250-200 – Power Spectrum of the filtered sound of Configurations A, D, E, and F

Comparison of the mechanical vibration and the noise of the bow on shooting

Figures 10 to 13 compare the power spectrum of the mechanical vibrations recorded at Position 3 and the sound of the bow for the 250-0 weight version of Configuration A (no damping) and Configuration D. Figures 10 and 11 show the recorded signals with no filters applied to the vibrations. Figures 12 and 13 show the effect of filtering the mechanical vibrations (lowpass filter at 500 Hz) and the sound (A-Weighted filter) to approximate the human perception of the vibrations of the bow. Analysing Figure 11 compared to Figure 10, illustrates that introducing damping on the bow reduces the amplitude of the vibrations and sound over the entire frequency range. Figure 13 compared to Figure 12 shows the effect of introducing damping on the bow as perceived by the archer. The introduction of damping reduces the vibrations in the high-frequency range for both the mechanical vibrations (for frequencies higher than 400 Hz) and the sound (for frequencies higher than 600 Hz). Considering human physiology, the archer is sensitive to mechanical vibrations lower than 500 Hz (on the hand-wrist-arm-shoulder structure) and the sensitivity of the human ear is strongly dependent on the tonal pitch [29], with the highest sensitivity between 2,000 Hz and 5,000 Hz [31]. According to this analysis, the archer should find it easier to appraise the change in sound intensity from an undamped to a damped configuration than the change in mechanical vibrations.

The other weight configurations show similar behaviour.

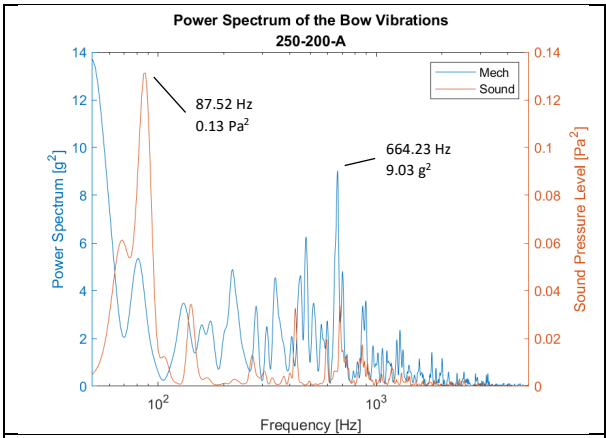


Figure 10 – Power spectrum of the mechanical vibrations (blue) and sound (red) for Configuration 250-200-A, no filter applied

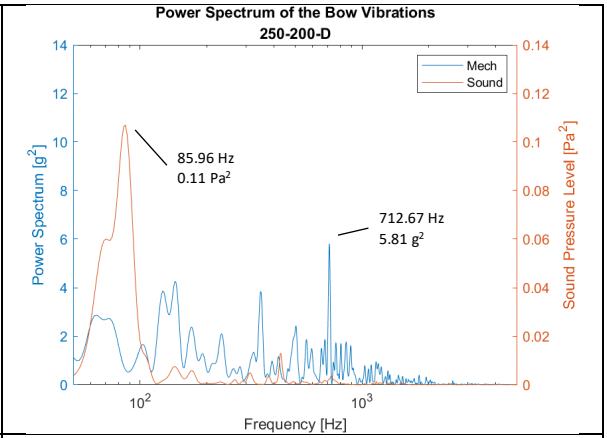


Figure 11 - Power spectrum of the mechanical vibrations (blue) and sound (red) for Configuration 250-200-D, no filter applied

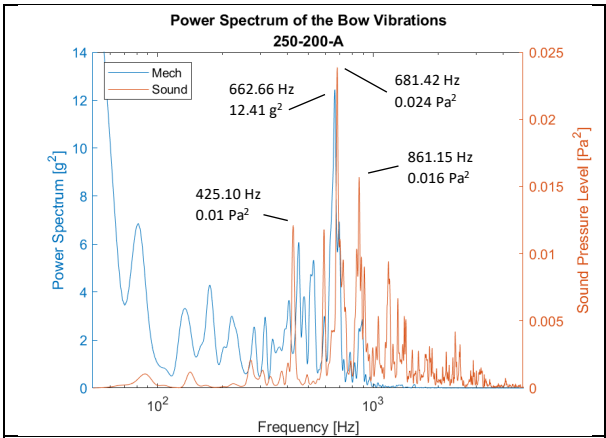


Figure 12 - Power spectrum of the mechanical vibrations (blue) and sound (red) for Configuration 250-200-A, lowpass filter at 500 Hz and A-Weighted filter applied

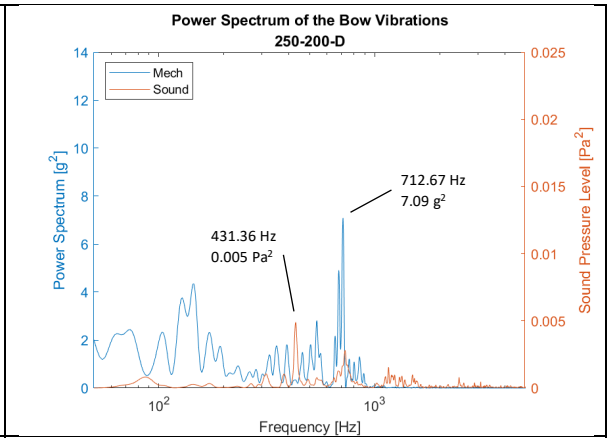


Figure 13 - Power spectrum of the mechanical vibrations (blue) and sound (red) for Configuration 250-200-D, lowpass filter at 500 Hz and A-Weighted filter applied

Subjective metrics: perceived mechanical vibrations and sound

To correlate subjective and objective matrices, a questionnaire, divided into four questions, was prepared:

- The perceived vibration level of the bow on shooting was evaluated using a Likert scale ranging from 1 “very high vibrations” to 5 “very low vibrations”.
- The perceived sound level of the bow on shooting was evaluated using a Likert scale ranging from 1 “very noisy” to 5 “very quiet”.
- The perceived sound quality of the bow on shooting was evaluated using a Likert scale ranging from 1 “very high pitch” sound (corresponding to a sound with a high-frequency content) to 5 “very low pitch” sound (corresponding to a sound with a low-frequency content).
- The perceived overall quality of the weight configuration on shooting was evaluated using a Likert scale ranging from 1 “very low quality” to 5 “very high quality”. The quality of the weight configuration refers to how much the archer appreciated the weight configuration, and how he/she liked the shooting experience.

It is assumed that a five-point Likert scale is sensitive enough to capture the archers’ experiences in shooting the different weight configurations. Furthermore, it is assumed that the scale is equally spaced between the five steps. This assumption is necessary to calculate the correlations between subjective and objective metrics and to answer the research questions, but it is an approximation of a more complex reality.

Eight archers from Archers of the Zoo Lake Club, Johannesburg, South Africa participated in the study, all of them considered to be at the Intermediate Level (proficiency evaluations based on the Archers of the Zoo Lake Club guidelines [32]). To better differentiate between vibration perception and sound perception, the archers were divided into pairs: one archer shooting the bow (“archer”) and the other archer listening to the sound of the bow (“observer”). The “archer” wore earplugs to reduce the sound of the bow on shooting and was requested to evaluate the vibration level of the bow and the quality of the weight configuration. The “observer” was requested to evaluate the sound of the bow both in intensity and pitch. After the conclusion of the tests, the pair swapped roles and the tests were run again.

Due to limited testing time, not all fifty-one weight configurations could be tested. Based on previous work by the authors [9], five good-performing weight configurations were selected, one single-weight (350-0) and four double-weight configurations (200-250, 250-200, 350-200 and 350-250). Regarding the damped configurations, Configurations A, C, and E (refer to Table 1) were chosen for the single-weight configuration while Configurations A, D, and E (refer to Table 2) were chosen for the double-weight configuration. Configuration A was chosen as a reference (configuration with no damping) while Configurations C and E (single weight), and D and E (double weight) were chosen as the best-

performing configurations in terms of vibration measurement at Position 3 for single and double tests, respectively. Table 6 reports the selected weight and damping configurations.

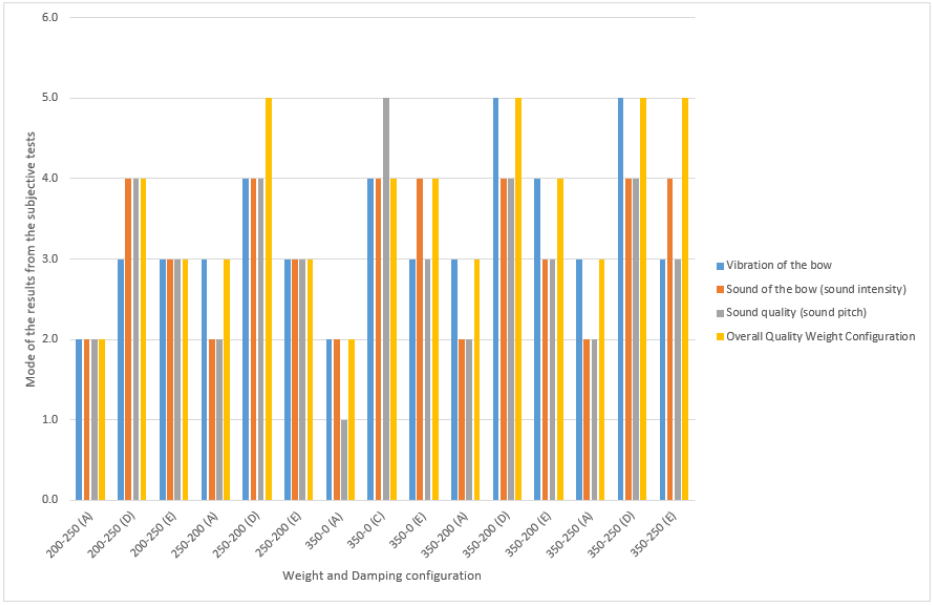
Table 6 – Selected weight configuration for subjective tests

Tested Weight configurations		
Single Weight configurations	Double Weight configurations	
350-0 (A)	200-250 (A)	350-200 (A)
350-0 (C)	200-250 (D)	350-200 (D)
350-0 (E)	200-250 (E)	350-200 (E)
	250-200 (A)	350-250 (A)
	250-200 (D)	350-250 (D)
	250-200 (E)	350-250 (E)

During the tests, the weight and damping configurations on the central and lower attachments were covered so that the "archer" and the "observer" could not see the configuration being tested. The testing sequence of the weight configurations was randomised for each test. The reference weight configuration used as the baseline for the subjective tests was Configuration B. The collected data are reported in Appendix C. Table 7 reports the mode, median and mean of the answers collected in the questionnaire, where the mode is the value of the most frequent score, the median is the middle value when observations are ordered from least to most and the mean is the average of all scores, calculated by adding all scores and then dividing by the number of scores [33].

Table 7 – Questionnaire results

	Vibration of the bow			Sound of the bow (sound intensity)			Sound quality (sound pitch)			Overall Quality Weight Configuration		
Weight configuration	Mode	Median	Mean	Mode	Median	Mean	Mode	Median	Mean	Mode	Median	Mean
200-250 (A)	2.0	2.0	2.13	2.0	2.0	2.00	2.0	2.0	2.25	2.00	2.00	2.25
200-250 (D)	3.0	3.5	3.50	4.0	4.0	3.63	4.0	4.0	3.63	4.00	3.50	3.38
200-250 (E)	3.0	3.0	3.00	3.0	3.0	3.13	3.0	3.0	2.75	3.00	3.00	3.25
250-200 (A)	3.0	3.0	2.63	2.0	2.0	2.00	2.0	2.0	2.13	3.00	3.00	3.00
250-200 (D)	4.0	4.0	4.38	4.0	4.0	3.88	4.0	4.0	3.75	5.00	5.00	4.63
250-200 (E)	3.0	3.0	3.13	3.0	3.0	3.25	3.0	3.0	2.88	3.00	3.50	3.63
350-0 (A)	2.0	2.0	1.88	2.0	2.0	1.75	1.0	1.0	1.38	2.00	2.00	1.75
350-0 (C)	4.0	4.0	4.38	4.0	4.5	4.50	5.0	4.5	4.25	4.00	4.00	3.88
350-0 (E)	3.0	3.0	3.13	4.0	4.0	3.63	3.0	3.0	3.25	4.00	3.50	3.38
350-200 (A)	3.0	3.0	2.63	2.0	2.0	2.13	2.0	2.0	2.38	3.00	3.00	3.25
350-200 (D)	5.0	5.0	4.63	4.0	4.0	4.00	4.0	4.0	4.13	5.00	5.00	4.63
350-200 (E)	4.0	3.5	3.50	3.0	3.0	3.25	3.0	3.0	3.25	4.00	4.00	4.00
350-250 (A)	3.0	3.0	3.00	2.0	2.0	2.13	2.0	2.0	2.25	3.00	3.00	3.25
350-250 (D)	5.0	5.0	4.50	4.0	4.0	4.25	4.0	4.0	4.25	5.00	5.00	4.88
350-250 (E)	3.0	3.5	3.63	4.0	3.5	3.38	3.0	3.5	3.63	5.00	4.50	4.38



Data analysis shows that the damped configurations scored better than the undamped Configuration A in all four subjective metrics. The "archer" perceived reduced mechanical vibrations for the damped configurations and appreciated these configurations more. The "observer" perceived a quieter bow and a lower frequency sound for the damped configurations. Regarding the single-weight configurations, both "archer" and "observer" consider Configuration C to be better than Configuration E, and Configuration D to be better than Configuration E for the double-weight configurations.

Discussion

The correlation between objective and subjective metrics was studied by evaluating the Pearson correlation coefficient r and the percentage of proportion of predictable variability $V = r^2$ [33]. The Pearson coefficient r was calculated considering the mode of the subjective metric. A Pearson correlation coefficient of $r > 0.5$ indicates a direct correlation, while $r < -0.5$ indicates an inverse correlation. The coefficient V, normally referred to as the Coefficient of Determination, is a measure of the proportion of total variability in one variable that is predictable from its relationship with the other variables [33] or, in other words, it gives an idea of the ratio of data points close to the line formed by the regression equation. The calculation of the coefficients of determination for the subjective metrics is based on the assumption of a linear Likert scale describing the perceptions of the archers. A coefficient of determination of $V > 0.25$ indicates a strong relationship, $0.09 < V < 0.25$ indicates a moderate relationship and $V < 0.01$ indicates a weak relationship [33]. The correlation coefficients between metrics are reported in the correlation matrix in Table 8. The objective and subjective metrics of interest are reported in the horizontal heading of the correlation matrix. The same metrics are reported on the vertical heading of the correlation matrix. The correlation coefficient between a specific metric with any other metrics is reported at the intersection of the corresponding row and column. For example, the correlation coefficients for the metric P2P (first row) are 1.00 with the metric P2P (first column), 0.87 with the metric RMS (second column), 0.81 with the metric Filtered P2P (third column), etc. The correlation matrix is symmetric about the main diagonal and the terms on the main diagonal are always 1.00 (perfect correlation of the metric with itself). The coefficients of determination V are reported in Table 9 in a matrix structure similar to the matrix of correlation coefficients.

All objective metrics show a high level of correlation within the same group. The metric "Decay Time" shows only a moderate correlation with the "Microphone" metrics. The "Microphone" metrics and the "Acceleration" metrics also show a high degree of correlation. All subjective metrics show a high level of correlation within that group; the archer perceived the quality of the weight configuration as an inverse function of the mechanical vibration of the bow on shooting, the intensity of the sound of the bow on shooting, and the pitch of the sound of the bow on shooting where the lower the pitch, the better the quality.

The analysis of the correlation between objective and subjective metrics (Table 8) shows interesting results. The subjective "Vibrations" and the objective "Accelerations" show a mixed moderate-to-strong inverse correlation, due to the scoring method decided for the subjective metric. "Filtered P2P" shows a relatively higher correlation than the unfiltered "P2P", in agreement with the results of earlier work [9], while the "Filtered RMS" shows a lower correlation compared to the unfiltered "RMS". The proposed explanation is that for the damped configurations, the difference between filtered and unfiltered RMS is too small to be appreciated by the archer (the data are reported in Appendix D). The subjective "Sound Intensity and Quality" and the objective "Microphone" metrics show an inverse correlation due to the scoring method decided for the subjective metric. The archer is capable of discerning the intensity and frequency content of the sound of the bow on shooting, and the quieter the bow, and the lower the frequency of the sound, the better the shooting experience. The same conclusions could be drawn by analysing the correlation between the subjective "Overall Quality" and the objective "Microphone" metrics. The analysis of the correlation between the subjective "Overall Quality" and the objective "Acceleration" metrics shows that a better-perceived quality of the weight configuration is related to the unfiltered RMS on Position 3. Interestingly the correlation between

"Overall Quality" and "Accelerations" is similar to the correlation between "Overall Quality" and "Sound", meaning that the perceived quality of the weight configuration depends on both the mechanical vibration of the bow and the sound of the bow on shooting. The metrics "Sound Intensity", "Sound Quality" and "Acceleration" show a stronger inverse correlation compared to the metrics "Vibrations" and "Microphone". These results suggest that is easier for the archer to perceive the vibration of the bow as radiated sound on shooting, instead of as mechanical acceleration on the riser. The subjective metric "Vibrations" shows a strong inverse correlation with the objective metric "Decay Time", while "Sound Intensity" and "Sound Quality" show a medium inverse correlation with the "Decay Time". The archers are aware of the time-to-rest of the string and the longer the time, the worse the shooting experience. The archers evaluate the vibration of the bow considering both mechanical vibrations ("RMS" and "Filtered RMS") and the time-to-rest of the bow ("Decay Time"). The metric "Damage" is strongly correlated to all other metrics (apart from the metric "Decay Time") as a demonstration of its importance as an objective metric.

Table 8 - Correlation matrix. Pearson correlation coefficients (r) between objective and subjective metrics

		Acceleration - Position 3					Microphone			Posi-tion 3	Subjective metrics			
		P2P [g]	RMS	Filtered P2P [g]	Filtered RMS	Damage	Max SPL	RMS	Leq	Decay Time [s]	Vibrations	Sound Intensity	Sound Quality	Overall Quality
Acceleration - Position 3	P2P [g]	1.00	0.87	0.81	0.68	0.64	0.69	0.75	0.75	0.04	-0.30	-0.78	-0.65	-0.58
	RMS		1.00	0.89	0.92	0.90	0.79	0.83	0.83	0.15	-0.56	-0.79	-0.80	-0.71
	Filtered P2P [g]			1.00	0.88	0.82	0.54	0.62	0.62	-0.08	-0.42	-0.65	-0.57	-0.63
	Filtered RMS				1.00	0.98	0.66	0.68	0.68	-0.04	-0.49	-0.56	-0.65	-0.60
	Damage					1.00	0.73	0.71	0.71	0.06	-0.55	-0.55	-0.70	-0.60
Microphone	Max SPL						1.00	0.97	0.97	0.47	-0.51	-0.71	-0.80	-0.62
	RMS							1.00	1.00	0.46	-0.52	-0.78	-0.83	-0.65
	Leq								1.00	0.46	-0.52	-0.78	-0.83	-0.65
Posi-tion 3	Decay Time [s]									1.00	-0.51	-0.40	-0.47	-0.34
Subjective metrics	Vibrations										1.00	0.64	0.74	0.81
	Sound Intensity											1.00	0.88	0.87
	Sound Quality												1.00	0.77
	Overall Quality													1.00

Table 9 – Coefficients of Determination (V) between objective and subjective metrics

		Acceleration - Position 3					Microphone			Position 3	Subjective metrics			
		P2P [g]	RMS	Filtered P2P [g]	Filtered RMS	Damage	Max SPL	RMS	Leq	Decay Time [s]	Vibrations	Sound Intensity	Sound Quality	Overall Quality
Acceleration - Position 3	P2P [g]	1.00	0.77	0.66	0.46	0.40	0.48	0.56	0.56	0.00	0.09	0.61	0.43	0.34
	RMS		1.00	0.80	0.84	0.81	0.63	0.69	0.69	0.02	0.32	0.62	0.65	0.51
	Filtered P2P [g]			1.00	0.78	0.67	0.29	0.38	0.38	0.01	0.18	0.42	0.33	0.39
	Filtered RMS				1.00	0.96	0.44	0.46	0.46	0.00	0.24	0.31	0.42	0.35
	Damage					1.00	0.53	0.51	0.51	0.00	0.30	0.30	0.48	0.37
Microphone	Max SPL						1.00	0.94	0.94	0.22	0.26	0.51	0.63	0.39
	RMS							1.00	1.00	0.21	0.27	0.61	0.69	0.43
	Leq								1.00	0.21	0.27	0.61	0.69	0.43
Position 3	Decay Time [s]									1.00	0.26	0.16	0.22	0.11
Subjective metrics	Vibrations										1.00	0.40	0.55	0.65
	Sound Intensity											1.00	0.77	0.76
	Sound Quality												1.00	0.59
	Overall Quality													1.00

The analysis of the coefficients of determination V (Table 9) shows that the data for the metrics within the groups “Acceleration”, “Microphone” and the subjective metrics “Sound Intensity”, “Sound Quality” and “Overall Quality” are strongly aligned with the regression line. The metrics “Microphone” compared to the metrics “Acceleration” show a strong relationship, as well as the subjective metrics “Sound Intensity”, “Sound Quality” and “Overall Quality” compared to the metrics “Acceleration” and “Microphone”. Better alignment exists between the “Vibrations” and the “Microphone” metrics compared to the “Vibrations” and the “Acceleration” metrics. These results confirm that is easier for the archer to differentiate the weight configurations by the radiated sound on shooting (intensity and frequency content) compared to the mechanical acceleration on the riser. This finding agrees with the expectation raised previously, based on human psychology.

Conclusion

The effect of damping was studied by considering both subjective and objective metrics to evaluate the effect of different damped configurations on the vibration and sound of a bow, and the archer's perceptions of the overall shooting experience. The results show that any form of damping on the bow decreases the mechanical vibrations and the sound intensity, with the best results for specifically designed damping devices, such as the vibration damper for the single-weight configuration and the Dampering for the double-weight configuration. The introduction of damping to the bow tends to effectively reduce the high-frequency components of the mechanical vibration and of the radiated sound while having little influence on the low-frequency components of the vibrations. The results for the subjective metrics show that the archers perceive a reduction in vibrations, sound intensity and sound pitch for the damped solutions. The reduction in these subjective metrics is associated with a better experience in shooting the bow. This research clearly shows that the introduction of damping improves the shooting experience.

This work also shows that a pure performance-based approach (objective metrics) is not enough to capture the complexity of the archer-bow interaction. Analysis of the correlations between objective and subjective metrics provides a deeper insight into the problem. This knowledge can be used to design better archery equipment from both the performance and user experience perspectives.

Disclaimer

The study was approved by the Human Research Ethics Committee (Non-Medical) of the University of the Witwatersrand to include the use of human participants. The three documents used in this study, the Introduction letter, the Consent form and the Questionnaire, are part of the ethics protocol defined in the Research Ethics document H22/01/25 which was approved by the Human Research Ethics Committee (Non-Medical) of the University of the Witwatersrand on the 28th of January 2022. All participants in the research were fully aware of being part of the tests for the collection of data for this academic study, and all participants signed the Consent form reported in the Research Ethics document H22/01/25.

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Declaration of Conflicting Interests

The Authors declare that there is no conflict of interest.

Data

All data used in the paper will be available on request. Please contact the main author by email.

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Appendix A

The following data are reported in the Global coordinate system. P2P is the root sum of squares of the P2P in the three directions X, Y and Z. RMS is the root sum of squares of the RMS in the three directions X, Y and Z, as well as Damage (D) is the root sum of squares of the Damages in the three directions X, Y and Z. P2P and RMS data are in units of g (standard Earth acceleration), Decay Time is in seconds while the Damage is dimensionless. The mechanical vibration data were filtered with a lowpass filter at 500 Hz.

Position 1

Configuration 200 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	1520.96	1526.68	1506.66	1516.52	1484.98
P2P - Y	1179.16	1185.82	1121.23	1142.85	1137.23
P2P - Z	761.20	666.39	667.55	652.90	763.49
P2P	2069.58	2044.75	1993.19	2008.04	2020.24
RMS - X	116.61	114.31	98.59	114.18	106.05
RMS - Y	82.52	81.42	70.23	78.90	75.38
RMS - Z	46.56	40.89	35.68	36.06	43.40
RMS	150.25	146.18	126.19	143.40	137.16
D - X	23443	21441	16953	21919	18470
D - Y	17170	16258	12478	15676	14326
D - Z	11169	9813	7869	8325	9413
D	31131	28641	22473	28204	25199
Decay Time	0.209	0.222	0.080	0.162	0.129

Configuration 250 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	1653.17	1639.85	1652.38	1625.33	1611.74
P2P - Y	967.36	947.44	939.08	945.45	934.86
P2P - Z	742.68	673.32	642.42	676.34	761.83
P2P	2054.34	2010.00	2006.22	1998.25	2012.97
RMS - X	133.92	131.45	107.13	128.30	123.40
RMS - Y	73.02	71.24	59.65	70.30	67.94
RMS - Z	43.24	39.12	35.53	40.30	40.66
RMS	158.54	154.55	127.66	151.75	146.62
D - X	24602	24763	17377	24307	21396
D - Y	13767	13713	10265	13509	12241
D - Z	10413	9050	8200	8831	8713
D	30054	29718	21785	29177	26144
Decay Time	0.245	0.213	0.105	0.213	0.178

Configuration 350 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	1665.61	1665.15	1697.89	1645.69	1580.11
P2P - Y	976.36	955.09	959.64	957.74	917.64
P2P - Z	733.55	629.53	608.53	679.89	653.60
P2P	2065.35	2020.20	2043.05	2021.83	1940.62
RMS - X	149.21	138.60	109.89	132.51	118.55
RMS - Y	80.66	74.18	60.27	72.48	65.34
RMS - Z	43.34	35.95	34.58	41.78	38.39
RMS	175.07	161.26	130.02	156.71	140.70
D - X	30456	27815	19745	23882	19757
D - Y	16663	14973	11216	13602	11311
D - Z	10075	8075	7938	9350	8600
D	36148	32604	24056	29031	24336
Decay Time	0.205	0.182	0.118	0.214	0.182

Configuration 200 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1624.99	1598.40	1618.09	1634.95	1670.48	1649.45
P2P - Y	957.08	924.38	927.32	973.83	996.39	972.52
P2P - Z	966.17	495.89	554.13	550.15	572.64	885.12
P2P	2118.98	1911.87	1945.56	1980.93	2027.61	2109.48
RMS - X	114.44	112.53	114.35	104.87	110.15	119.47
RMS - Y	64.92	61.47	62.91	58.74	61.00	67.92
RMS - Z	49.68	30.87	33.21	27.29	32.34	44.05
RMS	140.64	131.88	134.67	123.26	130.00	144.31
D - X	22547	20787	20458	17880	18231	23453
D - Y	13158	11581	11582	10303	10559	13583
D - Z	10788	7338	8363	6236	7725	8169
D	28247	24901	24952	21558	22440	28307
Decay Time	0.218	0.183	0.182	0.208	0.195	0.183

Configuration 200 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1607.65	1611.70	1573.79	1675.16	1658.79	1635.53
P2P - Y	917.22	915.04	909.57	927.37	932.67	929.52
P2P - Z	1057.46	558.51	569.40	464.74	640.29	937.83
P2P	2131.67	1935.67	1904.82	1970.32	2007.84	2102.02
RMS - X	111.46	115.27	120.97	103.00	104.16	111.57
RMS - Y	63.30	63.61	66.54	56.78	58.12	62.64
RMS - Z	51.23	35.49	35.98	29.26	38.07	42.66
RMS	138.04	136.36	142.68	121.19	125.21	134.88
D - X	21297	19988	21846	17265	17757	20651
D - Y	11848	11285	12151	9534	10027	11395
D - Z	12494	8450	9119	6983	9169	7956
D	27387	24460	26610	20922	22359	24892
Decay Time	0.221	0.187	0.182	0.168	0.155	0.208

Configuration 250 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1606.92	1624.00	1605.46	1629.87	1636.85	1645.45
P2P - Y	949.91	921.79	916.28	979.17	977.06	962.62
P2P - Z	886.24	517.51	645.90	669.24	745.82	840.07
P2P	2066.38	1937.75	1958.12	2015.72	2046.99	2083.24
RMS - X	117.06	113.84	108.77	103.97	112.06	116.43
RMS - Y	64.88	62.20	59.19	59.75	62.68	65.52
RMS - Z	45.17	32.03	36.57	32.34	38.13	40.37
RMS	141.26	133.62	129.12	124.20	133.94	139.56
D - X	23321	20269	19194	17887	19053	20692
D - Y	12834	11391	10610	10717	11173	11979
D - Z	10888	7425	7881	6885	9681	8325
D	28760	24408	23304	21959	24116	25317
Decay Time	0.218	0.183	0.183	0.183	0.144	0.159

Configuration 250 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1573.86	1586.96	1621.07	1666.03	1654.05	1594.86
P2P - Y	905.17	899.22	928.94	919.90	920.19	903.23
P2P - Z	1049.23	497.30	571.38	491.13	487.25	846.31
P2P	2096.96	1890.60	1953.79	1965.47	1954.49	2018.82
RMS - X	114.59	116.13	122.49	100.15	102.36	107.32
RMS - Y	65.41	63.68	67.32	55.12	56.44	60.13
RMS - Z	52.53	33.72	37.56	27.54	31.68	39.93
RMS	142.02	136.67	144.72	117.59	121.11	129.33
D - X	23013	21831	23674	16436	16200	20134
D - Y	13035	12062	13086	8937	9128	11203
D - Z	11800	8650	9975	6135	7646	7925
D	28961	26399	28831	19689	20106	24366
Decay Time	0.291	0.192	0.199	0.136	0.128	0.176

Configuration 350 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1579.60	1540.65	1520.57	1577.82	1577.77	1555.66
P2P - Y	907.46	863.82	993.52	923.14	928.64	900.21
P2P - Z	961.37	493.49	661.37	547.19	735.94	701.64
P2P	2059.81	1833.94	1933.03	1908.17	1973.15	1929.44
RMS - X	122.62	112.80	104.15	102.38	114.15	114.62
RMS - Y	68.01	60.30	63.22	55.71	62.53	62.49
RMS - Z	51.64	31.33	38.67	27.90	35.61	33.53
RMS	149.42	131.68	127.82	119.85	134.94	134.79
D - X	24640	21053	18632	17778	20546	20351
D - Y	14052	11167	11995	9549	11385	11207
D - Z	12181	7758	8517	6416	9369	7319
D	30870	25062	23739	21176	25289	24358
Decay Time	0.232	0.273	0.183	0.182	0.158	0.183

Configuration 350 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1545.70	1555.83	1577.92	1602.05	1581.26	1573.24
P2P - Y	883.10	885.32	893.87	897.76	892.37	887.71
P2P - Z	927.72	545.06	548.39	571.99	621.55	667.09
P2P	2007.41	1871.22	1894.61	1923.46	1919.13	1925.65
RMS - X	114.21	112.42	113.82	104.40	112.48	110.63
RMS - Y	63.50	61.69	62.60	57.53	61.58	60.65
RMS - Z	48.76	35.27	35.07	30.58	34.35	35.59
RMS	139.48	133.00	134.55	123.06	132.76	131.09
D - X	22270	20805	20593	16851	21429	19780
D - Y	12183	11540	11585	9234	11489	10892
D - Z	13094	8925	8556	7475	8178	7888
D	28563	25410	25130	20618	25654	23918
Decay Time	0.254	0.196	0.165	0.140	0.200	0.183

Position 2

Configuration 200 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	340.06	363.46	278.84	346.98	278.30
P2P - Y	277.96	287.89	269.39	256.60	241.83
P2P - Z	401.32	440.08	382.57	376.93	339.07
P2P	594.94	639.26	544.68	572.98	500.91
RMS - X	26.62	27.14	18.82	26.73	18.75
RMS - Y	15.39	15.51	13.47	15.09	12.91
RMS - Z	22.17	22.42	26.09	20.82	19.32
RMS	37.90	38.47	34.88	37.09	29.86
D - X	5625	5378	3325	5483	3290
D - Y	2845	2790	2210	2740	2130
D - Z	4835	3440	3570	3635	4225
D	7944	6967	5356	7126	5763
Decay Time	0.244	0.154	0.142	0.181	0.161

Configuration 250 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	361.87	360.40	268.19	338.09	316.35
P2P - Y	268.64	277.58	268.65	257.64	242.49
P2P - Z	435.38	396.05	350.22	354.93	413.09
P2P	626.64	603.15	516.48	553.77	574.04
RMS - X	27.39	25.86	17.93	27.51	19.72
RMS - Y	15.70	16.03	13.28	15.50	13.11
RMS - Z	21.48	23.65	23.38	19.46	19.88
RMS	38.18	38.53	32.32	37.09	30.91
D - X	5738	5205	3183	5775	3435
D - Y	2925	2920	2190	2928	2170
D - Z	4255	3371	3203	3428	3973
D	7719	6854	5018	7326	5682
Decay Time	0.220	0.166	0.139	0.225	0.133

Configuration 350 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	379.89	362.88	306.25	351.60	306.56
P2P - Y	261.52	253.34	265.78	244.82	227.04
P2P - Z	389.89	349.85	349.13	350.77	289.85
P2P	603.92	564.14	535.09	553.71	479.10
RMS - X	30.33	28.39	17.44	30.11	18.87
RMS - Y	15.89	15.76	13.52	15.47	11.97
RMS - Z	21.88	20.64	22.06	20.04	18.35
RMS	40.63	38.48	31.20	39.33	28.91
D - X	6450	5753	3250	6274	3420
D - Y	2955	2840	2435	2960	2060
D - Z	4790	3525	3013	3820	3825
D	8560	7320	5056	7919	5529
Decay Time	0.217	0.214	0.092	0.218	0.141

Configuration 200 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	364.55	388.40	473.13	277.96	309.59	293.20
P2P - Y	233.17	254.32	274.60	159.60	186.25	181.71
P2P - Z	502.73	364.87	380.36	333.38	354.21	297.41
P2P	663.32	590.47	666.28	462.47	505.96	455.45
RMS - X	23.38	24.36	24.03	17.81	20.32	18.86
RMS - Y	13.07	13.21	13.71	8.77	9.55	10.04
RMS - Z	27.27	17.75	18.88	18.42	23.23	19.47
RMS	38.22	32.91	33.49	27.08	32.31	28.90
D - X	4151	4440	4535	3108	3720	3360
D - Y	1849	2270	2448	1399	1425	1490
D - Z	5829	2863	3310	4233	5105	4038
D	7391	5750	6125	5434	6475	5460
Decay Time	0.163	0.095	0.110	0.143	0.207	0.167

Configuration 200 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	378.00	373.04	407.02	265.24	276.85	305.32
P2P - Y	230.49	234.29	292.22	176.11	166.71	174.90
P2P - Z	640.59	368.21	329.40	289.74	343.72	341.12
P2P	778.70	574.14	599.64	430.49	471.79	490.08
RMS - X	25.21	23.97	25.59	17.13	18.55	19.35
RMS - Y	13.83	12.64	13.75	9.12	9.47	10.05
RMS - Z	32.99	17.43	17.07	18.74	26.41	20.11
RMS	43.76	32.22	33.70	26.98	33.63	29.66
D - X	4583	4241	4785	2935	3500	3465
D - Y	2330	2255	2480	1424	1588	1468
D - Z	7215	2900	3305	4185	5570	3863
D	8859	5611	6322	5306	6767	5392
Decay Time	0.151	0.180	0.148	0.144	0.208	0.144

Configuration 250 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	346.62	397.21	452.55	307.24	322.74	317.94
P2P - Y	248.42	243.77	264.72	164.81	194.59	198.60
P2P - Z	450.68	478.70	526.08	438.64	364.29	401.40
P2P	620.46	668.10	742.72	560.32	524.15	549.22
RMS - X	24.31	25.89	22.28	18.96	20.54	19.65
RMS - Y	13.27	12.94	12.17	8.11	10.13	9.77
RMS - Z	27.15	19.40	22.35	19.50	19.27	21.65
RMS	38.78	34.85	33.83	28.38	29.93	30.83
D - X	4841	4575	3995	3278	3658	3485
D - Y	2245	2390	2248	1115	1470	1330
D - Z	6385	3238	3862	3733	3504	4153
D	8321	6093	5994	5091	5274	5582
Decay Time	0.143	0.143	0.095	0.123	0.160	0.155

Configuration 250 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	406.42	360.58	403.47	268.45	262.55	308.61
P2P - Y	197.21	227.66	241.92	169.73	176.73	161.42
P2P - Z	418.67	406.99	289.86	277.79	321.67	384.76
P2P	615.92	589.48	552.57	421.95	451.26	518.98
RMS - X	24.13	22.69	23.96	17.34	17.64	20.53
RMS - Y	12.81	11.57	12.87	8.84	9.22	9.34
RMS - Z	24.83	18.82	16.25	16.02	22.82	19.83
RMS	36.92	31.67	31.68	25.21	30.28	30.03
D - X	4421	4013	4365	2930	3355	3728
D - Y	1946	1744	2280	1425	1523	1365
D - Z	5583	2866	3190	3174	5605	4125
D	7382	5230	5868	4548	6707	5725
Decay Time	0.188	0.212	0.135	0.161	0.213	0.143

Configuration 350 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	337.35	370.29	442.42	285.07	316.31	305.19
P2P - Y	242.32	279.63	254.28	151.07	188.74	168.99
P2P - Z	454.51	431.22	564.83	414.60	358.23	457.73
P2P	615.71	633.45	761.20	525.34	513.81	575.51
RMS - X	24.86	23.37	24.21	18.77	21.30	19.63
RMS - Y	13.13	11.75	12.26	7.82	9.67	8.32
RMS - Z	24.82	19.41	23.45	20.45	20.85	21.96
RMS	37.50	32.57	35.87	28.84	31.33	30.61
D - X	4755	4013	4185	3285	4016	3450
D - Y	2110	2075	2210	1290	1314	1263
D - Z	5345	3070	3805	4425	4665	4358
D	7459	5462	6073	5660	6294	5699
Decay Time	0.164	0.144	0.095	0.144	0.143	0.179

Configuration 350 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	364.02	374.58	380.77	293.73	337.40	308.24
P2P - Y	233.75	256.18	229.36	151.67	194.00	144.04
P2P - Z	371.56	333.97	432.86	353.24	368.70	433.24
P2P	570.27	563.46	620.45	483.80	536.11	550.86
RMS - X	24.28	24.04	24.62	19.36	21.99	19.85
RMS - Y	13.04	11.83	12.24	8.67	9.51	8.57
RMS - Z	21.33	16.75	19.86	17.92	20.43	20.39
RMS	34.85	31.60	33.92	27.77	31.49	29.72
D - X	4485	4110	4590	3330	4305	3638
D - Y	1661	1898	2303	1443	1406	1328
D - Z	3529	2675	3428	3438	4408	3910
D	5944	5258	6174	4999	6320	5503
Decay Time	0.185	0.144	0.099	0.114	0.166	0.143

Position 3

Configuration 200 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	352.27	354.50	326.79	356.29	323.67
P2P - Y	88.97	75.42	86.43	75.89	94.28
P2P - Z	235.55	169.24	153.81	171.27	254.99
P2P	433.00	400.00	371.38	402.54	422.70
RMS - X	21.52	20.49	18.70	20.81	20.94
RMS - Y	8.22	5.97	5.02	6.06	7.44
RMS - Z	20.70	13.77	10.08	13.46	19.59
RMS	30.97	25.40	21.83	25.52	29.63
D - X	4005	3542	3120	3525	3915
D - Y	1858	1416	953	1371	1735
D - Z	4778	3223	1938	2990	4713
D	6505	4994	3794	4821	6368
Decay Time	0.148	0.088	0.117	0.104	0.127

Configuration 250 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	341.32	349.10	351.58	342.79	327.64
P2P - Y	79.95	72.79	77.99	76.71	78.27
P2P - Z	249.32	193.16	169.39	193.11	262.87
P2P	430.18	405.57	397.97	400.85	427.29
RMS - X	21.59	20.52	19.25	19.26	20.36
RMS - Y	8.55	6.14	5.19	6.29	7.31
RMS - Z	23.06	14.80	11.67	15.22	21.87
RMS	32.73	26.04	23.10	25.34	30.76
D - X	4106	3555	2993	3210	3724
D - Y	2104	1416	1073	1445	1733
D - Z	5880	3238	2385	3280	5295
D	7474	5013	3974	4811	6701
Decay Time	0.128	0.111	0.096	0.097	0.116

Configuration 350 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	335.65	331.62	346.60	320.35	300.74
P2P - Y	77.68	69.54	67.59	78.04	81.57
P2P - Z	248.23	172.75	169.72	207.86	280.76
P2P	424.63	380.33	391.80	389.77	419.43
RMS - X	21.57	18.81	19.17	17.85	18.69
RMS - Y	8.69	5.95	4.69	6.78	6.65
RMS - Z	24.24	13.86	11.82	16.73	21.37
RMS	33.59	24.11	23.00	25.38	29.16
D - X	4260	3285	3248	2985	3645
D - Y	2118	1309	998	1510	1505
D - Z	6206	3025	2473	3720	5081
D	7820	4653	4202	5003	6432
Decay Time	0.143	0.108	0.104	0.102	0.117

Configuration 200 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	366.65	358.74	352.25	289.43	321.60	325.48
P2P - Y	111.13	53.58	65.07	44.64	43.48	99.59
P2P - Z	241.02	127.07	210.60	116.20	100.51	242.82
P2P	452.63	384.34	415.53	315.06	339.73	418.11
RMS - X	21.71	19.44	18.70	17.08	17.98	19.77
RMS - Y	7.63	4.21	4.80	3.62	3.62	6.71
RMS - Z	18.16	9.14	12.48	8.95	9.04	16.49
RMS	29.31	21.89	22.99	19.62	20.45	26.61
D - X	3855	2993	2963	2719	2745	3338
D - Y	1708	868	919	697	833	1293
D - Z	4063	2060	2578	1990	2218	3283
D	5855	3735	4033	3441	3626	4856
Decay Time	0.116	0.113	0.078	0.151	0.139	0.125

Configuration 200 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	364.29	362.79	346.93	264.75	299.51	326.38
P2P - Y	110.55	62.21	60.25	64.41	65.55	104.59
P2P - Z	228.12	161.34	165.16	144.12	146.60	238.03
P2P	443.81	401.89	388.93	308.24	339.84	417.28
RMS - X	21.81	19.31	18.92	15.84	17.63	20.89
RMS - Y	7.48	4.70	4.73	4.89	4.43	7.05
RMS - Z	16.77	10.74	11.48	10.80	10.97	16.35
RMS	28.51	22.59	22.63	19.79	21.23	27.45
D - X	3525	3045	2933	2450	2665	3638
D - Y	1538	929	925	910	983	1341
D - Z	3698	2255	2715	2459	2640	3248
D	5335	3901	4102	3588	3878	5057
Decay Time	0.099	0.113	0.117	0.118	0.198	0.125

Configuration 250 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	355.85	367.35	357.46	295.52	325.50	331.98
P2P - Y	79.75	55.82	66.71	87.46	99.93	102.07
P2P - Z	215.88	166.40	233.22	229.82	255.19	315.99
P2P	423.78	407.13	431.99	384.45	425.51	469.56
RMS - X	20.56	19.17	18.51	19.12	19.33	20.84
RMS - Y	5.61	4.26	4.81	6.14	6.98	6.75
RMS - Z	15.86	10.44	13.49	15.51	17.44	19.40
RMS	26.57	22.24	23.41	25.37	26.96	29.26
D - X	3664	2849	2963	3218	3458	3645
D - Y	1205	880	971	1300	1509	1335
D - Z	3535	2035	2660	3080	3825	4050
D	5232	3610	4098	4640	5372	5610
Decay Time	0.175	0.093	0.177	0.102	0.107	0.098

Configuration 250 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	360.31	360.23	344.42	266.30	270.45	317.07
P2P - Y	124.82	59.69	63.21	44.18	57.26	102.77
P2P - Z	305.44	164.77	193.28	105.92	150.63	289.06
P2P	488.57	400.60	399.97	289.98	314.82	441.19
RMS - X	22.47	19.12	18.47	16.47	16.40	21.62
RMS - Y	9.02	4.53	4.92	3.24	3.98	7.09
RMS - Z	21.56	10.80	12.64	8.77	10.76	16.77
RMS	32.43	22.42	22.92	18.94	20.01	28.26
D - X	3964	2940	2820	2443	2700	3525
D - Y	1831	854	1018	694	820	1360
D - Z	5134	2195	2828	2108	2636	3510
D	6739	3767	4121	3300	3862	5157
Decay Time	0.118	0.117	0.117	0.089	0.120	0.095

Configuration 350 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	325.91	336.79	338.71	284.07	311.99	315.54
P2P - Y	71.77	62.58	68.76	84.46	92.40	79.52
P2P - Z	198.85	168.27	214.59	208.02	210.87	318.00
P2P	388.47	381.65	406.82	362.08	387.74	454.99
RMS - X	17.83	17.84	17.79	18.53	18.13	20.93
RMS - Y	5.17	4.68	5.05	5.94	6.52	4.82
RMS - Z	13.57	10.90	13.13	13.03	14.78	16.66
RMS	23.00	21.43	22.68	23.42	24.29	27.18
D - X	2870	2654	2678	3057	2930	3668
D - Y	1144	935	985	1141	1379	921
D - Z	3171	2199	2748	2641	3620	3249
D	4428	3571	3961	4198	4857	4985
Decay Time	0.134	0.092	0.077	0.097	0.163	0.071

Configuration 350 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	338.05	351.90	324.07	304.36	310.63	328.28
P2P - Y	124.29	54.52	63.73	85.44	54.79	64.52
P2P - Z	260.31	136.07	243.40	173.53	121.45	335.03
P2P	444.40	381.21	410.28	360.62	337.99	473.47
RMS - X	20.06	18.81	16.57	18.74	17.03	22.67
RMS - Y	8.35	4.04	4.74	5.69	4.38	4.71
RMS - Z	19.84	8.86	14.59	10.59	10.90	18.23
RMS	29.42	21.19	22.58	22.26	20.69	29.47
D - X	3488	2978	2205	3090	2640	3885
D - Y	1677	854	923	1126	921	878
D - Z	4650	1884	2988	2249	2713	3645
D	6050	3625	3826	3984	3896	5399
Decay Time	0.117	0.208	0.117	0.076	0.150	0.086

Position 4

Configuration 200 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	698.19	684.03	410.50	817.07	578.35
P2P - Y	382.36	323.68	264.37	371.55	288.42
P2P - Z	606.49	505.46	340.40	304.98	493.20
P2P	1000.75	910.03	595.21	947.98	812.97
RMS - X	30.71	30.94	22.55	28.86	24.94
RMS - Y	18.19	17.56	14.41	16.60	14.37
RMS - Z	20.79	22.18	19.26	17.26	15.58
RMS	41.31	41.93	32.97	37.50	32.73
D - X	5698	5355	3893	4549	4309
D - Y	3249	3148	2425	2955	2415
D - Z	2852	2610	2775	2425	1900
D	7152	6738	5360	5942	5292
Decay Time	0.092	0.080	0.078	0.051	0.082

Configuration 250 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	740.61	897.92	440.22	686.09	534.61
P2P - Y	370.17	324.73	288.24	359.59	304.87
P2P - Z	720.41	362.65	556.50	529.76	408.03
P2P	1097.50	1021.38	765.87	938.44	738.41
RMS - X	31.88	31.12	22.97	28.25	25.62
RMS - Y	18.52	17.03	13.70	17.40	14.82
RMS - Z	21.33	19.91	19.42	18.76	15.78
RMS	42.59	40.68	33.06	38.12	33.54
D - X	6169	5093	3686	4728	4245
D - Y	3350	3035	2273	3028	2410
D - Z	2893	2379	2600	2658	1745
D	7593	6388	5051	6212	5184
Decay Time	0.090	0.074	0.075	0.076	0.089

Configuration 350 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	808.86	799.97	455.66	853.78	364.69
P2P - Y	324.26	343.69	326.69	343.27	248.90
P2P - Z	712.59	397.86	418.28	386.68	336.45
P2P	1125.69	957.27	699.51	998.15	555.11
RMS - X	32.98	31.36	24.89	31.16	22.52
RMS - Y	19.22	18.63	15.43	18.35	15.30
RMS - Z	21.68	20.09	21.43	17.91	15.86
RMS	43.90	41.64	36.29	40.35	31.51
D - X	6124	4969	4343	5085	3990
D - Y	3517	3385	2525	3354	2673
D - Z	2835	2393	3000	2704	2129
D	7610	6471	5851	6664	5253
Decay Time	0.095	0.075	0.082	0.074	0.122

Configuration 200 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	278.14	472.77	611.31	292.25	369.22	236.12
P2P - Y	217.43	288.16	329.70	225.14	214.34	177.18
P2P - Z	701.71	556.66	500.18	357.19	496.35	476.26
P2P	785.51	785.12	855.91	513.50	654.70	560.33
RMS - X	19.72	19.66	20.78	16.67	18.13	16.07
RMS - Y	14.65	14.29	14.85	12.05	12.02	10.89
RMS - Z	30.63	17.58	16.20	16.04	18.81	21.08
RMS	39.26	29.99	30.25	26.08	28.76	28.65
D - X	3068	3108	3240	2669	3395	2783
D - Y	2090	2343	2468	2196	1973	1913
D - Z	4033	2048	2139	2421	3180	4208
D	5481	4397	4600	4220	5053	5395
Decay Time	0.294	0.067	0.062	0.087	0.131	0.185

Configuration 200 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	234.73	551.27	609.10	336.40	433.94	219.92
P2P - Y	190.64	337.46	354.03	229.67	234.57	185.31
P2P - Z	494.21	547.44	460.32	297.76	479.42	466.45
P2P	579.39	847.04	841.56	504.55	687.88	547.98
RMS - X	17.41	19.38	19.89	17.77	23.13	14.40
RMS - Y	13.75	14.87	14.15	12.55	14.14	11.15
RMS - Z	27.47	18.30	15.22	13.68	18.82	21.24
RMS	35.31	30.52	28.77	25.70	33.00	27.98
D - X	3270	2600	2713	2995	4436	2560
D - Y	2876	2285	2335	2315	2640	1915
D - Z	5918	2101	2418	2181	2881	4035
D	7347	4049	4319	4369	5912	5148
Decay Time	0.213	0.042	0.046	0.078	0.078	0.214

Configuration 250 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	344.12	433.87	459.78	311.73	324.66	282.59
P2P - Y	258.95	280.01	307.13	208.19	208.04	206.37
P2P - Z	701.87	695.40	633.48	384.39	514.53	456.93
P2P	823.46	866.16	840.84	536.92	642.98	575.53
RMS - X	20.04	19.40	19.99	18.41	19.73	18.10
RMS - Y	14.16	14.83	15.22	11.73	11.91	11.16
RMS - Z	25.87	24.94	20.43	18.18	23.00	20.05
RMS	35.65	34.90	32.38	28.41	32.56	29.23
D - X	3350	2930	3163	3133	3555	3028
D - Y	2083	2420	2467	1998	1949	1691
D - Z	4286	1996	2458	3103	4984	3553
D	5825	4293	4704	4840	6424	4965
Decay Time	0.253	0.074	0.069	0.077	0.120	0.159

Configuration 250 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	258.69	385.87	773.42	356.07	349.45	247.82
P2P - Y	210.39	253.46	311.35	244.94	234.02	214.61
P2P - Z	535.46	509.71	306.02	351.11	339.37	478.89
P2P	630.80	687.71	888.13	556.83	540.42	580.35
RMS - X	17.07	17.97	20.74	19.33	20.87	14.69
RMS - Y	13.79	13.98	13.41	13.42	13.76	12.05
RMS - Z	28.80	15.12	13.95	14.90	15.59	23.23
RMS	36.21	27.33	28.36	27.85	29.46	30.02
D - X	2940	2700	2650	3424	4060	2420
D - Y	2538	2268	2270	2455	2663	2330
D - Z	5400	1894	2385	2309	2546	4005
D	6652	4002	4227	4804	5482	5227
Decay Time	0.172	0.082	0.036	0.074	0.102	0.164

Configuration 350 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	406.52	543.46	750.07	271.73	341.43	276.26
P2P - Y	254.19	276.30	256.11	210.00	208.16	204.32
P2P - Z	817.99	741.02	454.47	328.74	493.86	518.54
P2P	948.15	959.58	913.64	475.40	635.45	622.06
RMS - X	21.19	20.91	21.31	16.53	20.37	16.61
RMS - Y	14.22	14.41	14.39	11.36	11.46	10.79
RMS - Z	29.43	24.08	18.75	17.12	23.14	17.98
RMS	38.95	34.99	31.82	26.37	32.89	26.75
D - X	3562	3105	3074	2460	3795	2660
D - Y	2392	2405	2445	1960	1864	1580
D - Z	5310	2019	2223	2943	4605	3040
D	6827	4416	4513	4307	6252	4337
Decay Time	0.113	0.061	0.042	0.095	0.119	0.143

Configuration 350 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	329.25	688.70	545.32	266.86	356.91	246.69
P2P - Y	222.01	379.77	320.31	220.36	234.19	204.01
P2P - Z	576.99	486.09	407.06	302.16	444.15	449.75
P2P	700.44	924.56	752.11	459.43	616.04	552.04
RMS - X	18.66	21.14	19.97	16.67	19.17	16.03
RMS - Y	13.09	14.84	13.95	12.22	13.40	11.18
RMS - Z	27.76	17.36	15.62	15.83	21.25	18.10
RMS	35.92	31.12	28.94	26.03	31.60	26.64
D - X	3258	3122	2915	2648	3398	2745
D - Y	2336	2380	2245	2130	2397	1833
D - Z	5640	2020	1994	2695	3788	2945
D	6919	4415	4185	4337	5625	4423
Decay Time	0.143	0.044	0.049	0.075	0.105	0.167

Position 5

Configuration 200 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	1789.59	1798.37	1568.65	1777.57	1696.04
P2P - Y	957.64	940.17	846.81	917.27	893.34
P2P - Z	489.56	468.03	394.22	433.32	504.20
P2P	2087.91	2082.57	1825.69	2046.68	1982.12
RMS - X	131.35	125.15	96.12	122.21	108.71
RMS - Y	72.31	67.12	52.90	64.71	59.49
RMS - Z	38.22	34.74	29.28	32.29	33.47
RMS	154.73	146.20	113.55	142.01	128.36
D - X	25697	23149	15566	22353	18205
D - Y	14402	12545	8678	11751	10371
D - Z	8792	7488	6548	6881	7250
D	30742	27373	18986	26174	22171
Decay Time	0.213	0.223	0.100	0.219	0.209

Configuration 250 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	1841.61	1835.88	1534.83	1888.13	1732.86
P2P - Y	949.38	950.70	829.27	984.33	920.56
P2P - Z	496.62	473.05	400.00	495.12	519.72
P2P	2130.61	2120.87	1789.81	2186.12	2029.86
RMS - X	134.81	130.65	93.99	132.83	111.67
RMS - Y	71.81	68.78	51.91	71.06	61.54
RMS - Z	36.83	33.53	29.63	36.80	35.68
RMS	157.12	151.41	111.38	155.07	132.40
D - X	25339	24021	14801	25036	18666
D - Y	13712	12676	8367	13654	10628
D - Z	8375	7325	6608	7775	7838
D	30003	28131	18241	29558	22865
Decay Time	0.223	0.214	0.132	0.228	0.214

Configuration 350 - 0

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E
P2P - X	1816.65	1850.53	1516.37	1819.62	1667.82
P2P - Y	939.37	959.99	807.28	952.62	924.00
P2P - Z	479.40	428.25	438.42	429.86	455.85
P2P	2100.58	2128.25	1772.93	2098.40	1960.40
RMS - X	144.80	130.41	95.65	125.45	106.09
RMS - Y	76.75	68.55	52.01	68.03	60.59
RMS - Z	36.97	31.59	30.61	35.17	34.22
RMS	168.00	150.67	113.09	146.98	126.87
D - X	28331	24554	16454	22944	17427
D - Y	15164	12831	9020	12821	10523
D - Z	8688	6875	7113	7356	7144
D	33288	28545	20067	27293	21574
Decay Time	0.228	0.227	0.168	0.219	0.182

Configuration 200 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1613.94	1621.80	1676.79	1405.73	1498.55	1438.26
P2P - Y	898.37	862.64	880.00	743.51	792.23	764.74
P2P - Z	591.98	525.93	459.01	432.24	471.57	495.33
P2P	1939.66	1910.76	1948.52	1647.94	1759.45	1702.58
RMS - X	111.25	107.52	110.46	91.80	104.02	105.82
RMS - Y	61.22	58.92	59.50	48.25	54.57	57.68
RMS - Z	46.50	35.62	32.54	29.03	33.67	31.97
RMS	135.23	127.68	129.61	107.70	122.19	124.69
D - X	20139	18002	18657	12634	17053	17770
D - Y	11314	10092	10217	7120	9396	9997
D - Z	12281	7488	6613	6694	8558	7438
D	26162	21954	22276	15972	21267	21703
Decay Time	0.245	0.237	0.237	0.164	0.172	0.237

Configuration 200 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1502.26	1653.39	1685.24	1277.38	1313.42	1336.55
P2P - Y	802.90	865.80	877.84	703.51	737.56	694.48
P2P - Z	511.26	395.39	409.88	435.46	479.20	402.64
P2P	1778.43	1907.78	1943.87	1521.92	1580.73	1559.10
RMS - X	109.04	111.00	113.46	89.56	98.85	91.37
RMS - Y	59.14	59.67	60.95	48.44	54.41	48.40
RMS - Z	37.33	28.77	30.08	31.64	33.19	29.78
RMS	129.54	129.26	132.26	106.62	117.61	107.60
D - X	17474	19249	18742	12607	15294	13150
D - Y	9904	10425	10151	7272	8797	7343
D - Z	9450	5749	6698	7354	7838	6961
D	22198	22633	22341	16306	19306	16592
Decay Time	0.197	0.228	0.251	0.168	0.203	0.190

Configuration 250 - 200

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1717.36	1684.83	1571.12	1510.84	1606.84	1553.61
P2P - Y	938.00	903.35	840.62	785.82	833.14	820.23
P2P - Z	497.99	461.38	526.40	513.00	509.66	392.90
P2P	2019.20	1966.61	1858.00	1778.57	1880.38	1800.24
RMS - X	120.86	112.86	105.00	93.59	105.02	110.86
RMS - Y	65.43	61.67	57.52	49.69	55.22	59.16
RMS - Z	36.69	30.04	35.25	31.46	33.61	28.89
RMS	142.25	132.07	124.80	110.53	123.32	128.94
D - X	22229	18828	18232	13894	17668	19919
D - Y	12275	10613	10129	7702	9612	10702
D - Z	9275	6276	7406	6938	8233	6334
D	27034	22506	22132	17334	21733	23482
Decay Time	0.272	0.219	0.196	0.167	0.209	0.245

Configuration 250 - 350

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1527.02	1669.79	1722.39	1291.32	1294.15	1414.42
P2P - Y	800.66	872.93	899.86	705.71	715.86	723.28
P2P - Z	511.03	398.55	401.49	373.80	437.30	404.51
P2P	1798.33	1925.89	1984.33	1518.31	1542.24	1639.31
RMS - X	100.48	110.08	113.99	86.81	92.56	90.43
RMS - Y	53.57	58.78	60.89	46.68	49.49	46.90
RMS - Z	39.49	28.55	30.21	27.73	31.38	27.21
RMS	120.52	128.01	132.71	102.39	109.55	105.44
D - X	16225	19045	19840	11709	13650	12893
D - Y	9011	10207	10634	6707	7695	6936
D - Z	10456	5685	6936	5960	7320	6588
D	21302	22343	23555	14752	17295	16055
Decay Time	0.336	0.228	0.242	0.240	0.168	0.181

Configuration 350 - 200

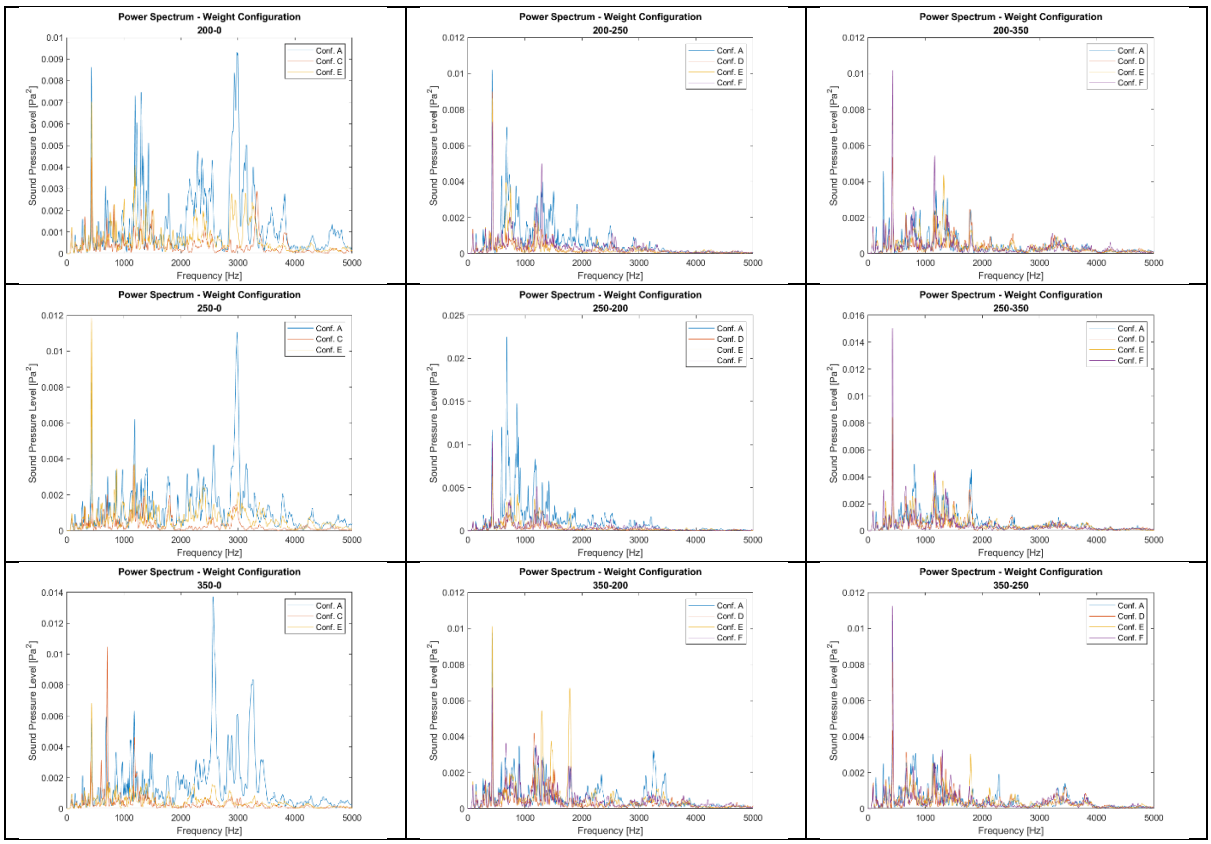
	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1681.68	1638.60	1495.94	1434.16	1639.43	1440.47
P2P - Y	914.01	870.42	812.39	764.33	846.56	784.42
P2P - Z	470.43	488.43	512.02	428.83	461.07	432.09
P2P	1970.98	1918.65	1777.63	1680.75	1901.83	1696.16
RMS - X	117.09	106.61	103.64	92.18	104.20	96.63
RMS - Y	63.14	58.12	57.57	49.04	54.58	52.61
RMS - Z	36.23	32.66	35.65	26.70	33.16	26.95
RMS	137.87	125.74	123.80	107.77	122.22	113.27
D - X	21944	18720	17396	12898	18143	15018
D - Y	11810	10384	10162	7171	9774	8312
D - Z	9363	7444	8181	5880	8333	5723
D	26621	22664	21744	15886	22229	18093
Decay Time	0.200	0.196	0.163	0.200	0.168	0.229

Configuration 350 - 250

	Conf. A	Conf. B	Conf. C	Conf. D	Conf. E	Conf. F
P2P - X	1654.99	1760.30	1683.29	1423.13	1576.26	1427.28
P2P - Y	849.61	926.71	893.39	742.72	813.20	747.97
P2P - Z	460.35	379.77	507.68	353.49	381.95	358.99
P2P	1916.44	2025.25	1972.14	1643.74	1814.32	1650.90
RMS - X	106.68	112.34	109.82	90.43	102.84	90.97
RMS - Y	55.98	59.71	58.79	47.06	52.67	47.61
RMS - Z	33.76	28.72	31.90	24.30	28.06	24.36
RMS	125.11	130.42	128.58	104.79	118.90	105.53
D - X	18573	19500	19004	12989	16545	13420
D - Y	10007	10537	10299	7151	8814	7230
D - Z	8533	5850	7300	5524	6596	5303
D	22757	22924	22815	15823	19873	16139
Decay Time	0.213	0.228	0.237	0.168	0.209	0.164

Appendix B

Power Spectrum of the sound of the bow on shooting for the different weight configurations. The sound signals were filtered with an A-Weighted filter.



Appendix C

The data from the Questionnaires are reported in the following tables. The columns “Scoring” from 1 to 8 report the evaluations from both the archer and the observer for the tested weight configurations. The mode (“Mode”) and the median (“Median”) are then calculated for the reported scores.

Vibration of the bow

Weight configuration	Scoring 1	Scoring 2	Scoring 3	Scoring 4	Scoring 5	Scoring 6	Scoring 7	Scoring 8	Mode	Median
200-250 (A)	1	2	2	3	2	2	3	2	2.0	2.0
200-250 (D)	3	4	4	4	3	3	4	3	3.0	3.5
200-250 (E)	3	3	3	4	3	2	4	2	3.0	3.0
250-200 (A)	3	2	2	3	3	2	3	3	3.0	3.0
250-200 (D)	5	5	4	4	4	4	5	4	4.0	4.0
250-200 (E)	4	2	3	4	3	3	3	3	3.0	3.0
350-0 (A)	2	2	2	2	1	2	2	2	2.0	2.0
350-0 (C)	4	5	5	4	5	4	4	4	4.0	4.0
350-0 (E)	3	4	4	4	2	3	2	3	3.0	3.0
350-200 (A)	2	2	3	3	3	2	3	3	3.0	3.0
350-200 (D)	5	4	5	4	5	4	5	5	5.0	5.0
350-200 (E)	4	3	4	4	3	3	3	4	4.0	3.5
350-250 (A)	3	2	3	3	4	3	3	3	3.0	3.0
350-250 (D)	2	5	5	5	5	4	5	5	5.0	5.0
350-250 (E)	3	5	4	4	3	3	3	4	3.0	3.5

Sound of the bow (sound intensity)

Weight configuration	Scoring 1	Scoring 2	Scoring 3	Scoring 4	Scoring 5	Scoring 6	Scoring 7	Scoring 8	Mode	Median
200-250 (A)	3	2	2	2	1	2	2	2	2.0	2.0
200-250 (D)	4	4	4	4	3	3	4	3	4.0	4.0
200-250 (E)	4	4	3	3	2	3	3	3	3.0	3.0
250-200 (A)	3	1	2	2	2	2	2	2	2.0	2.0
250-200 (D)	5	4	4	4	4	3	4	3	4.0	4.0
250-200 (E)	5	2	4	4	3	3	3	2	3.0	3.0
350-0 (A)	2	1	2	2	1	2	2	2	2.0	2.0
350-0 (C)	4	5	5	4	5	4	5	4	4.0	4.5
350-0 (E)	4	4	4	3	3	3	4	4	4.0	4.0
350-200 (A)	2	2	3	2	2	2	2	2	2.0	2.0
350-200 (D)	4	5	4	4	4	3	4	4	4.0	4.0
350-200 (E)	4	4	3	4	2	3	3	3	3.0	3.0
350-250 (A)	2	2	3	2	2	2	2	2	2.0	2.0
350-250 (D)	5	4	5	4	4	3	4	5	4.0	4.0
350-250 (E)	4	4	4	4	2	3	3	3	4.0	3.5

Sound quality (sound pitch)

Weight configuration	Scoring 1	Scoring 2	Scoring 3	Scoring 4	Scoring 5	Scoring 6	Scoring 7	Scoring 8	Mode	Median
200-250 (A)	3	3	2	2	2	2	2	2	2.0	2.0
200-250 (D)	4	4	4	4	4	3	3	3	4.0	4.0
200-250 (E)	4	3	3	3	3	2	2	2	3.0	3.0
250-200 (A)	3	2	2	2	2	2	2	2	2.0	2.0
250-200 (D)	4	4	4	4	4	3	4	3	4.0	4.0
250-200 (E)	4	2	3	3	3	2	3	3	3.0	3.0
350-0 (A)	1	1	1	2	2	2	1	1	1.0	1.0
350-0 (C)	5	3	5	4	5	3	5	4	5.0	4.5
350-0 (E)	3	4	3	3	3	3	4	3	3.0	3.0
350-200 (A)	2	3	3	2	3	2	2	2	2.0	2.0
350-200 (D)	4	5	5	4	4	3	4	4	4.0	4.0
350-200 (E)	4	4	3	3	4	2	3	3	3.0	3.0
350-250 (A)	2	2	3	2	3	2	2	2	2.0	2.0
350-250 (D)	5	5	5	4	4	3	4	4	4.0	4.0
350-250 (E)	5	5	3	3	4	2	3	4	3.0	3.5

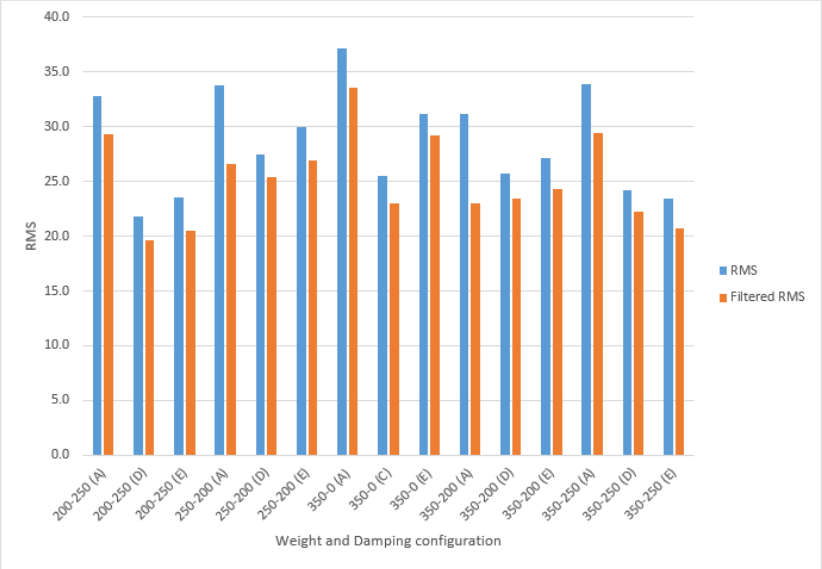
Overall Quality of the Weight Configuration

Weight configuration	Scoring 1	Scoring 2	Scoring 3	Scoring 4	Scoring 5	Scoring 6	Scoring 7	Scoring 8	Mode	Median
200-250 (A)	2	3	3	2	1	3	2	2	2.0	2.0
200-250 (D)	2	3	5	4	2	4	3	4	4.0	3.5
200-250 (E)	3	3	5	4	3	3	2	3	3.0	3.0
250-200 (A)	4	4	3	3	2	3	3	2	3.0	3.0
250-200 (D)	4	5	5	5	5	4	5	4	5.0	5.0
250-200 (E)	3	3	4	5	4	3	4	3	3.0	3.5
350-0 (A)	1	2	2	2	1	3	1	2	2.0	2.0
350-0 (C)	3	4	4	3	5	4	4	4	4.0	4.0
350-0 (E)	3	4	4	3	4	4	3	2	4.0	3.5
350-200 (A)	4	4	3	3	3	3	3	3	3.0	3.0
350-200 (D)	4	5	5	5	5	4	5	4	5.0	5.0
350-200 (E)	4	4	5	5	4	3	4	3	4.0	4.0
350-250 (A)	4	4	3	3	3	3	3	3	3.0	3.0
350-250 (D)	5	5	5	5	5	4	5	5	5.0	5.0
350-250 (E)	5	5	5	5	4	3	4	4	5.0	4.5

Appendix D

The following table shows the RMS calculated at Position 3 (*RMS*) compared to the same data filtered with the lowpass filter at 500 Hz (*Filtered RMS*). The data are reported for the 15 weight configurations tested in the subjective tests. The data are in unit of *g* (standard Earth acceleration).
The reported values for RMS and Filtered RMS are similar except for the five A configurations.

Acceleration - Position 3		
Weight configuration	RMS	Filtered RMS
200-250 (A)	32.8	29.3
200-250 (D)	21.8	19.6
200-250 (E)	23.5	20.4
250-200 (A)	33.8	26.6
250-200 (D)	27.5	25.4
250-200 (E)	29.9	27.0
350-0 (A)	37.1	33.6
350-0 (C)	25.5	23.0
350-0 (E)	31.2	29.2
350-200 (A)	31.2	23.0
350-200 (D)	25.7	23.4
350-200 (E)	27.1	24.3
350-250 (A)	33.9	29.4
350-250 (D)	24.2	22.3
350-250 (E)	23.4	20.7



4.5. Critical evaluation of the second paper and the methodology

Building on the foundation of the first paper, the selection of objective and subjective metrics was extended to form a comprehensive set of metrics. The introduction of the correlation matrix for the data analysis was a fundamental step in the development of the application of the methodology and was very successful in obtaining a deep understanding of the problem suggesting less than obvious relationships between the damping on the bow (design), the performance of the archery equipment (objective metrics) and the archers' sensations on shooting (subjective metrics).

The main finding of this study was that the introduction of damping to the bow tends to effectively reduce the high-frequency components of the mechanical vibration and of the radiated sound while having little influence on the low-frequency components of the vibrations. The analysis of the subjective metrics showed that the archers perceived a reduction in vibrations, sound intensity and sound pitch for the damped solutions, and the reduction in these subjective metrics was associated with a better experience in shooting the bow. The mixed research methodology was successful in showing that the introduction of damping (design change) reduced the vibrations of the bow (engineering measurements) while improving the shooting experience (archers' subjective perceptions). The methodology was also capable of suggesting the best damper solution for both single and double-weight configurations.

The next step in demonstrating the capabilities of the methodology was to consider a completely different problem. In the third paper, the limbs (the flexible part of the bow) were considered and analysed to determine relationships between design, objective and subjective metrics. It was decided to explore the third research approach for the mixed research methodology, the convergent mixed method. With this approach, the researcher converges or merges quantitative and qualitative data to provide a comprehensive analysis of the research problem. In this design, the investigator typically collects both forms of data at roughly the same time and then integrates the information in the interpretation of the overall results [1] [2].

Chapter 5

Analysis of the Correlations Between Subjective and Objective Metrics for Recurve Archery Limbs

5.1. Introduction

The third paper analysed the relationship between the design of the limbs (the flexible part of the bow, Figure 9), their performance in terms of engineering measurements (static quality coefficient, efficiency and dimensionless initial velocity) and the archers' perceptions on shooting. Limbs are produced in two versions: wood core and foam core and with two connection-to-the-riser systems: Formula and International Limb Fitting (ILF) systems. No scientific publications are available to guide archers in the decision as to which type of limbs to buy although their decision will affect their archery career for a long time due to the price of the limbs[10]. Another consequence of the limbs' price is that an archer is rarely capable of trying different manufacturing technologies or brands and the decision to purchase a set of limbs is normally based on unproven beliefs. Ten archers from the Archers of the Zoo Lake Club participated in the study. Of these, six were classified as Intermediate and four as Advanced archers. Within this third group of archers, two Intermediate and three Advanced archers participated in the first and the third investigations, while three Intermediate and three Advanced archers took part in the second and the third investigations.

The third study was about testing the mixed research methodology for a completely different part of the bow: the limbs (the flexible part of the bow). New objective and subjective metrics were defined describing the new problem from both the engineering and the archers' point of view. Nine sets of limbs were tested from four brands (Winner, Win&Win, Uukha and Hoyt), five poundages (30, 32, 36, 38, and 40 pounds of nominal draw weight[11]), two manufacturing technologies (wood and foam core) and two connection systems (International Limb Fitting (ILF) system and Formula). The extreme variability between the limbs required the development of novel strategies to group different limbs together and look at variations within the groups and across groups. In the administration of the questionnaire, great care was taken to prevent the archer's replies from being biased by the poundage

[10] From JVD Archery website (https://www.jvd-archery.com/, accessed on 23.04.2024), the price for a medium-quality set of limbs is between 222.50 and 599.00 euros and the price for a high-quality set of limbs is between 599.00 and 1,155.00 euros. JVD Archery is a world leading distribution partner for the archery industry.

[11] The poundage of the bow is the force apply from the limbs to the archer's finger in full draw. Since the poundage is function of the draw length, the nominal poundage of the limbs is defined at a standard 28 inches draw [10] [9].

of the limbs. The archers were requested to test and compare the limbs within poundage groups, one group at a time.

Also in the third study, the mixed research methodology was very effective in understanding the relationships between the design, the performance and the user sensations demonstrating its flexibility and efficacy in tackling these complex problems. The third study demonstrated that the proposed methodology is capable of analysing the relationships between performance, design details and user sensations for completely new components of the bow (the limbs).

5.2. Methodology

For the third study of this work, a convergent mixed methods design was used (QUAN + QUAL approach). With this approach, the researcher converges or merges quantitative and qualitative data to provide a comprehensive analysis of the research problem. In this design, the investigator typically collects both forms of data at roughly the same time and then integrates the information in the interpretation of the overall results [1] [2].

The quantitative (QUAN) research tool

The objective metrics considered in the study were the three quality coefficients defined by Kooi [33] [34], the stiffness and smoothness of the limbs, the level of vibration in the bow and the sound of the bow. Nine sets of limbs were tested from four brands. Seven sets of limbs had the ILF connection system and two had the Formula (see Third paper, Figure 9, page 87). All limbs were in the long version[12], with nominal poundages from thirty pounds (133.45 N) to forty pounds (177.93 N). The production year of the limbs spans four years with the possibility of evaluating the technological progress over this period of time. The risers used in the experiments were the Hoyt 2020 Xceed and the Hoyt 2020 Formula Xi, chosen because they were both 2020 risers, with the same handle but different connection systems. Using the same handle means that the archer can focus on the experience of using different limbs, minimising the distraction due to different risers. The weight of both risers was the same, 2.76 pounds (1,252 g)[13].

All objective metrics were measured in the Archery Laboratory, except for the sound of the bow on shooting. For the quality coefficients, the rig available in the laboratory was used (see Third paper, Figure 11, page 91). The level of vibration and the sound of the bow on shooting were recorded with a single archer (the author) shooting the various configurations, three shots per configuration. The

[12] All limbs are in the long version, meaning that when associated with a standard 25 inch riser (635 mm), they created a 70 inch bow (1778 mm).
[13] https://s3.hoyt.com/uploads/2019/3679900d28ff65a264e612c9f68ab4a4.pdf

sound of the bow on shooting was recorded outdoors, at the Archers of the Zoo Lake Club range, early in the morning to minimise interference from other noise sources.

The qualitative (QUAL) research tool

Six subjective metrics were chosen for the research: perceived stiffness, perceived smoothness, perceived speed of the limbs, mechanical vibrations, sound intensity, and preference. The decision about the subjective metrics was based on the experience accumulated with the first two studies. In the collection of the data, it was necessary to differentiate between stiffness and smoothness to avoid archers reporting the wrong perception during the tests. Ten archers from Archers of the Zoo Lake Club participated in the study. The archers were selected using the same criteria as in the first two studies, employing both purposive and convenience/opportunistic sampling methods. Unfortunately, a group of ten archers is not enough to reach saturation. Ten archers were all archers available for testing at the time of the research with the necessary characteristics: intermediate or advanced archers, equally divided between recurve and barebow archers. The limbs were divided into three groups to avoid bias in testing the limbs due to the different poundage: group 1 (nominal poundage between 30 and 32 pounds), group 2 (nominal poundage 36 pounds), and group 3 (nominal poundage between 38 and 40 pounds). The tests were organised for the same archer to shoot all limbs on the same day, testing the limbs according to the group. The order of the testing of the limbs was kept constant between archers. The archers were generally unaware of the manufacturing technology they were testing, while ILF and Formula limbs were easily recognisable.

A questionnaire was administered after the test of each configuration to collect the subjective metrics. Similar to the first two questionnaires in previous studies, the questionnaire was tested and refined by the three coaches of the Archers of the Zoo Lake Club. The questionnaire is available in Appendix E.

The same confounding variables [1] [2] [11] [12] identified in the first two investigations were considered and controlled, the only difference being the potential bias of the researcher. As an active archer, the author regularly trains with the tested equipment and has his preferences for poundage, brand and connection system. Everything was done to avoid any form of bias: the author never commented on the archers' answers and merely replied to technical questions when necessary. All limbs are of the same quality level and were very successful over the years with different Olympic archers, except for the Winner Motive C5, which are cheaper compared to the other and never competed in professional competitions.

In the third study, some data coding was necessary to compare objective and subjective data. All data coding is reported in the Third paper, Appendix C, pages 115 to 117. All data coding was based on the author's understanding of the problem and his experience as an archer and coach.

5.3. Contribution of the author to the third paper and contribution to knowledge

The idea of this paper dates back to the beginning of the PhD studies of the author, but it was considered too complex a problem to be suited to the initial phases of the development of the research methodology. It was decided to use this idea only for testing a fully developed methodology. The limbs are a complex problem to study due to their variability (draw poundages, manufacturing technologies and connection systems), the number of tests necessary to define their characteristics (objective metrics) and the extensive list of subjective metrics necessary in this study.

As for the first two papers, the author defined the subjective metrics for this third study, created the questionnaire to collect the subjective data and administered the questionnaire to ten archers of the Archers of Zoo Lake Club in September 2023. The questionnaire is available in Appendix E. The objective metrics were divided into a group of engineering measurements typically associated with the limbs and a group of quality coefficients. The first group was defined by the author while the second group was defined according to the literature [33] [34]. The tests on the objective metrics were executed from September to November 2023 by the author in the Archery Laboratory (MIA School, University of the Witwatersrand). The data analysis was a challenging task with the analysis of thirty-eight metrics divided into twelve subjective and twenty-six objective metrics. Leveraging on the experience gained with the previous investigations and the author's extensive knowledge in archery, meaningful correlations were found and a deeper understanding of the proposed problem was achieved. As for the first two papers, the discussions with Profs. Loveday and Reid were important in understanding the physical meaning behind the collected data. The writing of the paper was completed by the author in January 2024, and the paper was published in a third journal article with the title '*Investigation into the correlations between engineering measurements and archers' perceptions of different limbs in a recurve bow*'. The paper was published in Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology on the 27th of July 2024 (online publication).

Regarding the paper's contribution to knowledge, this third study demonstrates the effectiveness of the mixed research methodology in understanding complex problems involving engineering measurements, design and athletes' perceptions of sports equipment. The methodology was tested for a completely new problem and demonstrated its effectiveness in providing a deep understanding of the relationship between limb design, the archers' sensations on shooting, and the performance of

the limbs. All three research approaches typical of the mixed research methodology were tested: exploratory, explanatory, and convergent mixed methods designs have all been capable of providing insight into the researched problem.

The paper is available at the following link:

https://journals.sagepub.com/doi/abs/10.1177/17543371241258542

5.4. Third journal paper: Investigation into the correlations between engineering measurements and archers' perceptions of different limbs in a recurve bow

The following paper is in the "accepted manuscript" version, maintaining its original structure as submitted for publication. It is presented with single-line spacing to distinguish it from the rest of the thesis. The first page of the published version of the paper is available in Appendix A. Note no. 14 was added in this version and was not part of the original submitted document. The paper is reproduced under the terms of Sage's Author Archiving and Re-Use Guidelines. Please see Appendix G for details.

Title

Investigation into the correlations between engineering measurements and archers' perceptions of different limbs in a recurve bow

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Abstract

A novel methodology was developed to correlate the performance of different sets of archery limbs, chosen from different manufacturers, manufacturing technologies, and connection systems, to the sensations experienced by the archers using the bow. Objective metrics (measurable quantities) and subjective metrics (archers' sensations while using the equipment) were defined. These metrics were correlated to obtain a deeper understanding of the relationship between the metrics. Nine sets of limbs were tested to determine their static loading curve, speed of arrows on release, mechanical vibrations, and sound of the bow on shooting. The mechanical vibrations were measured at two positions on the bow. The limbs were tested by ten archers to evaluate the subjective metrics. Three quality coefficients were used that related to engineering measurements. These quality coefficients could be used to evaluate the relative performance of the limbs. The analysis of the correlations between objective and subjective metrics provides new insights into the problem, highlighting interesting relationships between engineering measurements and archers' sensations. The methodology used in this work was successful in fostering an understanding of the relationship between objective and subjective metrics on shooting. The results of this analysis could be used to improve existing designs or create new products for archery.

Keywords
Archery, archery limbs selection, subjective metrics, objective metrics, bow vibrations, bow sound, correlation, archer's experience.

List of Notation

DAQ	Data acquisition system
DFC	Draw Force Curve
ILF	International Limb Fitting system
L_{eq}	Equivalent Continuous Sound Level
Max SPL	Maximum Sound Pressure Level
MSV	Mean Squared value
P2P	Maximum to Minimum Difference
r	Pearson correlation coefficient
RMS	Root Mean Squared value
SPL	Sound Pressure Level
V	Coefficient of Determination

Introduction

The first scientific studies of archery were conducted in 1937 [1] and 1943 [2]. The insight gained from these early studies questioned the traditional English longbow design and initiated the process that would create the Olympic recurve bow. The Olympic recurve bow design is a hybrid between the English longbow and the traditional recurve bow (Turkish bow): while the tips of the limbs resemble the traditional recurve bow being initially bent in the opposite direction of the draw, the Olympic recurve bow is longer than the traditional recurve bow and similar in size to the longbow [3]. The modern Olympic recurve consists of a central rigid part called the "riser", two flexible parts called "limbs" and a string to connect the two tips of the limbs (Figure 1). The arrow is connected to the string and is supported by the arrow rests attached to the riser (Figure 2).

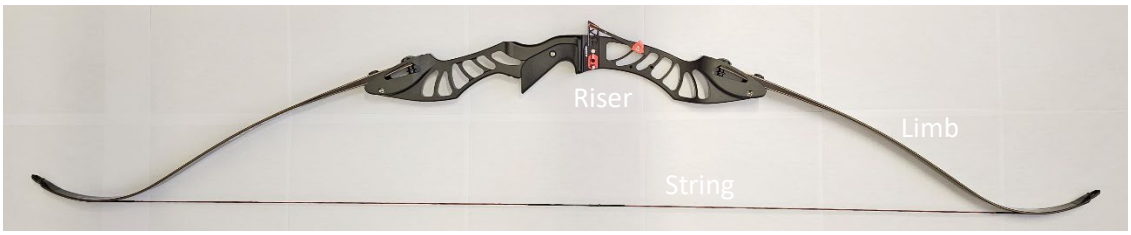


Figure 1 - The modern Olympic recurve bow. Hoyt Xceed 25 in riser with Win&Win NS Wood limbs

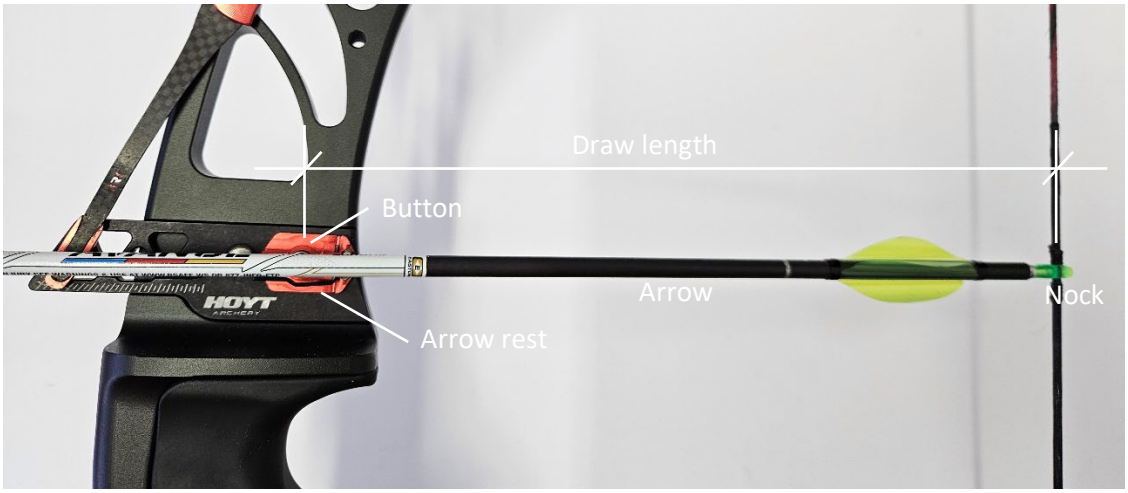


Figure 2 - The arrow is connected to the string by the nock and is resting on the arrow rest

The action of shooting the arrow comprises the following steps: the archer pulls the string from the rest position (brace height) to the maximum draw (full draw) deforming the limbs in the process. The string is released and the arrow accelerates leaving the string and the bow. The limbs are the only mechanism in the bow responsible for storing the potential energy caused by the deformation imposed by the draw of the arrow. The string is essentially inextensible and does not contribute to the storing of the potential energy in the bow[14] [3]. When the archer releases the string, the stored potential energy of the limbs is converted into the kinetic energy of the arrow. Several studies have attempted to mathematically describe the behaviour of the arrow between the release of the string and the arrow leaving the riser (defined as internal ballistic [3] [4] [5]) and the flight of the arrow toward the target (defined as external ballistic [3] [6] [7]). As illustrated in Figure 3, the evolution of the deformation of the limb as a function of the draw is quite complex. The tip of a recurve limb initially points in the opposite direction of the draw force (i.e., away from the archer). As the string is drawn, the tip begins to straighten and, at full draw, the tips are deformed in the direction of the draw force. This behaviour has significant advantages compared to the straight tips of the longbow because it guarantees greater potential energy stored in the limbs for the same draw [8]. Some authors have

[14] See Appendix H for the tests executed in the Archery Laboratory to support this statement.

mathematically described the change in the shape of the limbs between the brace height and the full draw for different types of bows: Hickman [1] and Kooi [9] for the English longbow; and Schuster [10] and Kooi [11] [12] [13] for the Olympic recurve bow. For the latter, the tip of the limb is represented by a circular arc which unrolls along the initial tangent as the bow is drawn, and the bow tip moves along a partial cycloid [10]. Although this geometrical representation of the tip displacement offers the possibility of simulating the draw, it is quite different from the real shape of the tip and the corresponding evolution of the shape of the limbs on draw (Figure 3).

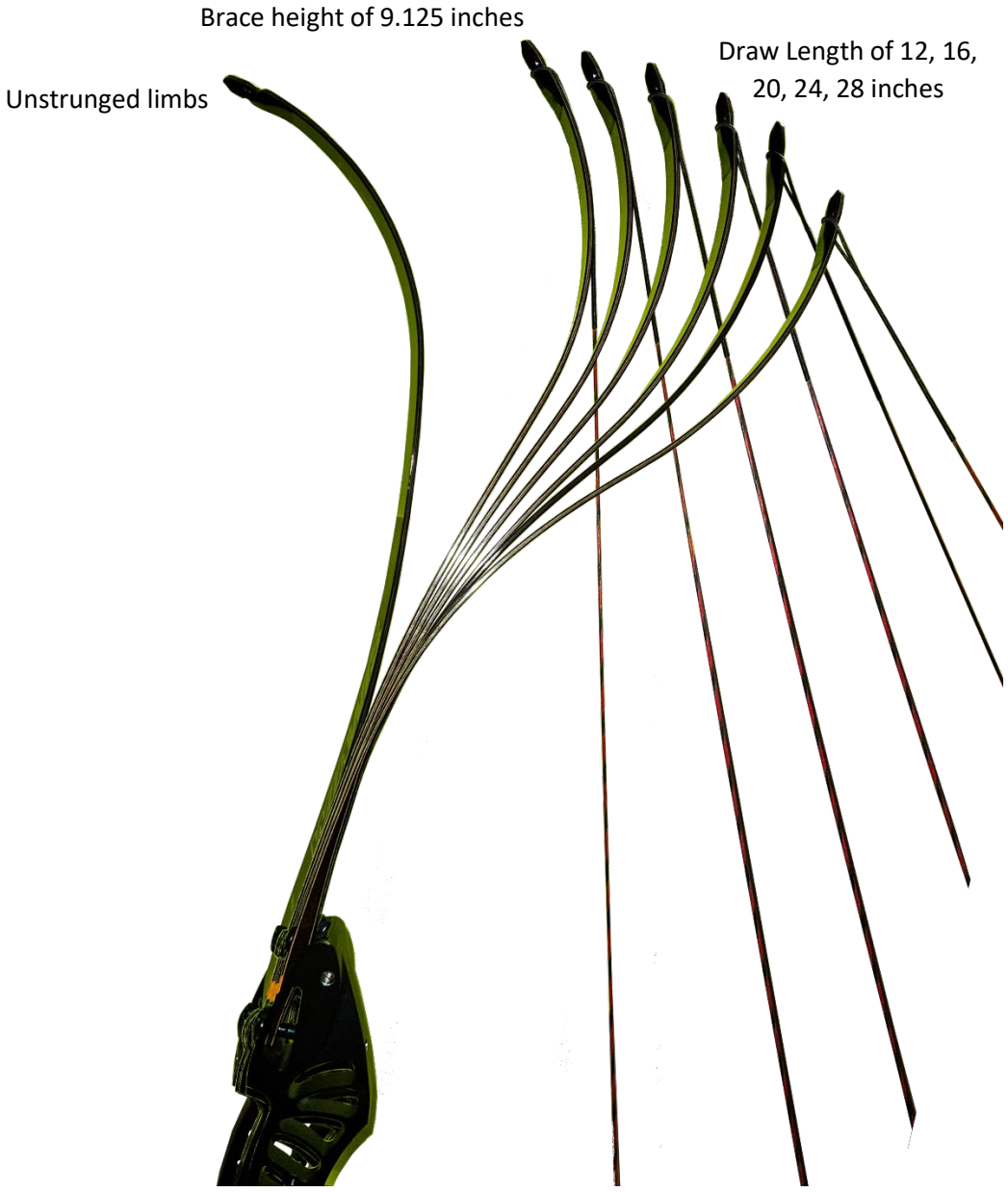


Figure 3 - Limb displacement at different draw lengths of an Olympic recurve bow. Limbs Win&Win NS Wood

Not all the stored potential energy is converted into kinetic energy in the arrow: some kinetic energy remains in the bow as limbs and string move during and after the shot [3].
The limbs can be studied considering three factors: the speed of the arrow, the stability and the smoothness of the limbs [14]. The speed of the arrow is related to the efficiency of the limbs, i.e., to their ability to convert potential to kinetic energy in the arrow. Stability is related to the accuracy and consistency of the limbs [14], where accuracy is the ability to minimize the error on shooting, while

consistency refers to the uniformity of shooting in different environmental conditions. Smoothness is related to the feeling of shooting: when the limbs are smooth, it is easier to draw the bow, aim and extend through the clicker [14] (the clicker is a device for ensuring constant draw length on release of the arrow). Kooi defined static and dynamic quality indicators to evaluate the performance of the limbs based on stored potential energy [11] and the speed of the arrow on shooting [9].
The limbs are normally manufactured using a laminating process: different layers of various materials are bonded together to create the required thickness and shape. Limbs for beginner archers are usually made from wood, foam and fibreglass (Figure 4); while high-performance limbs are manufactured using high-strength carbon fibres bonded to a foam core (Figure 5) or a wood core (Figure 6) [8] [15].



Figure 4 - Limbs Winner Motive C5 [16]



Figure 5 - Limbs Win&Win (WIAWIS) NS - Foam core [90]



Figure 6 - Limbs Win&Win (WIAWIS) NS - Wood core [90]

The carbon foam (in Figure 4 'Foam' and in Figure 5 'Foam Core') is typically lighter than wood (in Figure 6 'Wood Flax'), and thus allows a slightly more efficient bow, but wood typically has better damping properties, reducing vibration after the string is released [8]. Another less common manufacturing technology is a closed carbon fibre boxed shape used in the limbs of the brand Uukha (Figure 7) [18].



Figure 7 - On the top, a set of laminated limbs (Hoyt Axia). On the bottom, a set of boxed limbs (Uukha Sx+)

The limbs are connected to the riser using either the International Limb Fitting (ILF) system or the Formula system. Both systems have a U-shaped slot at the end of the limb (Figure 8, A) which fits under the main bolt on the riser (Figure 8, C), and a dovetail (Figure 8, B) that fits in the corresponding block on the riser (Figure 8, D). The shooting loads are transferred to the riser by the U-shaped-slot-to-main-bolt connection, while the dovetail allows for the alignment of the limbs relative to the riser. The main difference between ILF and Formula systems is that the distance between the dovetail and the U-shape is longer in the Formula system (Figure 9) [19]. Formula limbs also allow a damper to be directly attached to the limbs, using the bushing between the dovetail and the U-shape (Figure 9, E) [20].

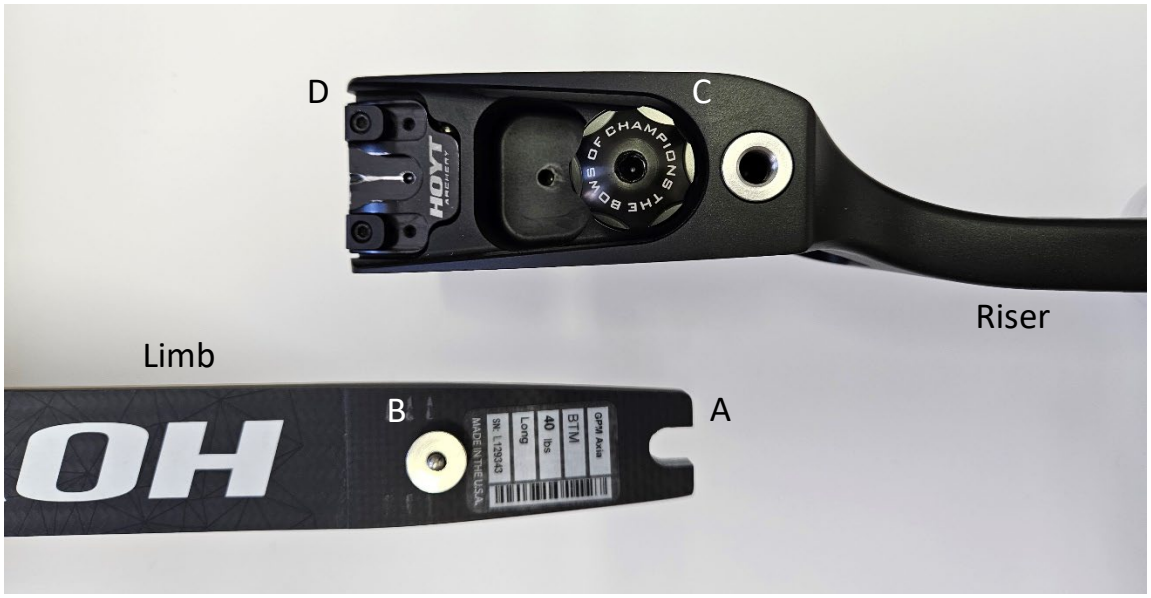


Figure 8 - U-shape 'A', dovetail 'B', main bolt 'C' and adjustment block 'D'

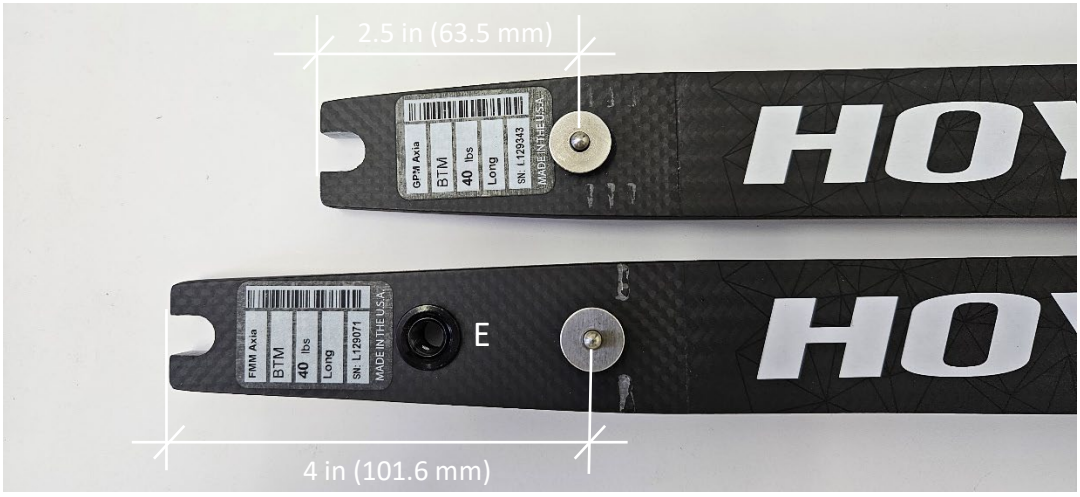


Figure 9 - ILF connection system (top) and the Formula connection system (bottom)

This work considers the effect of the different manufacturing technologies and connection systems on both objective (measurement) and subjective points of view (physical sensation while shooting). The intention is to understand what effects a measurable limb characteristic has on the archer's shooting experience.

Methods

In the following work, a two-fold methodology is developed to evaluate the performance of different sets of limbs selected from different manufacturers, manufacturing technologies, and connection systems. Initially, an engineering approach is developed which considers the quality coefficients defined by Kooi [9] [11]; the stiffness and smoothness of the limbs, the level of vibration in the bow, and the sound of the bow. Subsequently, an archer-centred approach is developed to evaluate the archers' experience of shooting with the different limbs. This two-fold approach is necessary when trying to understand problems that involve human experiences [21] [22]. The measurement of the performance of the limbs is useful from the engineering perspective (design of new equipment, optimization of shape and performance) but does not describe the archer's experience. Without considering the human aspect of the problem, the solution will be an interesting engineering exercise of limited value to the archery community.

The engineering approach was developed by defining objective metrics to be measured during the shooting of the arrow. Considering the draw of the string in the initial phase of the shooting sequence, a draw force vs. draw length graph can be plotted called the Draw Force Curve (DFC). The area under the curve is the potential energy stored in the limbs, while the first derivative or slope of the DFC is defined as the smoothness [8] with dimensions N/m. The stiffness of the limbs is the force exerted on the archer's finger at a particular draw length and is measured in N. These two definitions are commonly used in the archery environment and will be adopted in this paper for easy comparison between the engineering measurements and archers' experience. Considering the shooting phase, the speed of the arrow can be measured allowing the evaluation of the static quality coefficient [11], the efficiency of the limbs and the dimensionless initial velocity of the arrow [9]. These metrics will be defined later. The different manufacturing technologies supposedly affect the level of vibrations of the bow which can be further divided into mechanical vibrations and the sound of the bow on shooting [22]. Precision on target was not selected as an objective metric because of the impractical number of shots required to achieve statistical significance [23] [24].
The archer-centred approach was developed by administering a questionnaire to archers asking about their experience when using the bow with the same sets of limbs previously studied in the engineering approach. The questionnaire asked about the physical sensation of shooting with a particular set of limbs mounted on the riser. For this particular study, the archers were asked to evaluate the stiffness and the smoothness of the limbs, the speed of the limbs, the level of mechanical vibration of the bow, the intensity of the sound of the bow on release, and to evaluate the overall quality of each configuration (subjective metrics). The stiffness is related to the perceived force necessary to draw the string, while the smoothness is the perceived increase in draw force necessary for the corresponding increase in draw, evaluated for different draw lengths.
The study of the correlation between objective and subjective metrics gives insight into this problem seeking a relationship between what is measured and what is perceived by the archers. The correlations are studied by evaluating the Pearson correlation coefficient r and the coefficient of determination $V = r^2$ [25] between the defined metrics.

Experimental Set-Up

The risers used in the experiments were the Hoyt 2020 Xceed and the Hoyt 2020 Formula Xi (Figure 10) [26]. They were chosen because they were both launched into the market in 2020 and are similar, but have different connection systems. The handle used in both risers is the same, so the archer could focus on the experience of using different limbs, instead of being distracted by two different risers. The main bolts for both risers were set in a standard position as per Hoyt's recommendations. Both risers are provided with the Hoyt String Tension Technology [26] set on 'Hybrid'. The stabilisation system during the tests was limited to a simple 250 g weight attached to the central attachment of the riser (Figure 10, F). This configuration allowed for better behaviour of the bow on shooting compared to the simple riser, and minimal damping as reported by Pietra et al. [21] [22]. The bow was set up for the barebow style and tuned using the procedure described by Kaminsky [27]. Both bows were set with a brace height of 23.2 mm and a positive tiller of 3 mm. The lower part of the upper nocking point was set to 10 mm compared to the zero position (arrow rest position). No further tuning for individual archers was performed. To avoid inconsistency between the tests, gap-shooting was preferred as the aiming style compared to string-walking [19]. In the gap-shooting aiming style, the archer places the point of the arrow on a different area of the target to compensate for the shooting distance. In the string-walking aiming style, the archer places the point of the arrow on the centre of the target and increases the distance between the arrow and the index finger to compensate for the shooting distance. This latter aiming system was not utilised because it could change the tension of the lower limb and its mechanical vibrations.



Figure 10 - On the top in black, the Hoyt 2020 Xceed (ILF). On the bottom in red, the Hoyt 2020 Formula Xi (Formula)

The list of the limbs tested in the experiments is presented in Table 1. Nine sets of limbs were tested from four brands. Seven sets of limbs had the ILF connection system and two had the Formula. All limbs were in the *Long* version, meaning that associated with a standard 25-inch riser (635 mm), they created a 70-inch (1778 mm) bow. The *Nominal Poundage* is the force experienced by the archer's fingers when the string is drawn at 28 in (711.2 mm) draw length, and represents a measure of the stiffness of the limbs. The *Production Year* of the limbs span four years with the possibility of evaluating the technological progress over this period of time. The weights of the upper and lower limbs were measured to evaluate the Dimensionless Initial Velocity quality coefficient. All limbs had a brace height of 9.125 in (232 mm) according to the Hoyt manual [28] and the Win&Win manual [29], except for the Uukha Sx+, with a brace height of 8.875 in (225 mm) as specified by Uukha [18].

Table 1 - List of the limbs tested in this study

Name	Manufacturer	Website	Connection System	Length	Nominal Poundage [lb]	Production Year	Upper Limb Weight [g]	Lower Limb Weight [g]
Motive C5	Winner WNS	http://wns-archery.com/	ILF	Long	30	2019	228.24	228.94
NS Foam	Win&Win (WIAWIS)	https://www.wiawis.com/	ILF	Long	32	2018	177.26	176.18
NS Wood	Win&Win (WIAWIS)	https://www.wiawis.com/	ILF	Long	32	2018	183.22	183.42
SX+	Uukha	https://www.uukha.com/	ILF	Long	36	2021	188.14	189.84
Carbon Velos	Hoyt Archery	https://hoyttarget.com/	Formula	Long	36	2021	205.77	203.64
MXT-10 Foam	Win&Win (WIAWIS)	https://www.wiawis.com/	ILF	Long	38	2021	183.16	184.17
MXT-10 Wood	Win&Win (WIAWIS)	https://www.wiawis.com/	ILF	Long	38	2021	185.97	184.89
Axia Grand Prix	Hoyt Archery	https://hoyttarget.com/	ILF	Long	40	2022	190.15	191.40
Axia Formula	Hoyt Archery	https://hoyttarget.com/	Formula	Long	40	2022	207.18	209.15

Objective Metric: Quality Coefficients

The three quality coefficients defined by Kooi [11] [9] are the *Static Quality Coefficient* q, the *Shooting Efficiency* η and the *Dimentionless Initial Velocity* of the arrow v. The analysis of the quality coefficients gives insight into the difference between the tested limbs.

The Static Quality Coefficient q is defined as:

$$q = \frac{\bar{A}}{|\overline{OD}| \cdot \bar{F}(|\overline{OD}|)} \tag{1}$$

where $\bar{A}$ is the area under the DFC and evaluates the potential energy stored in the limbs, $|\overline{OD}|$ is the reference draw length, and $\bar{F}(|\overline{OD}|)$ is the draw force at the reference draw length. The area under the DFC $\bar{A}$ is defined as:

$$\bar{A} = \int_{\bar{b}=|\overline{OH}|}^{\bar{b}=|\overline{OD}|} \bar{F}(\bar{b}) \cdot d\bar{b} \tag{2}$$

where $\bar{b}$ is the draw and $|\overline{OH}|$ is the brace height.
The Shooting Efficiency η is defined as the kinetic energy (KE) imparted to the arrow divided by the potential energy (PE) of the bow before release:

$$\eta = \frac{KE}{PE} = \frac{\bar{m}_a \cdot \bar{c}_l^2}{\bar{A}} \tag{3}$$

Where $\bar{m}_a$ is half the mass of the arrow and $\bar{c}_l$ is the initial velocity of the arrow, which is measured.
The Dimensionless Initial Velocity v is defined as:

$$v = \sqrt{\frac{q \cdot \eta}{m_a}} = \sqrt{\left(\frac{\bar{A}}{|\overline{OD}| \cdot \bar{F}(|\overline{OD}|)}\right) \cdot \left(\frac{\bar{m}_a \cdot \bar{c}_l^2}{\bar{A}}\right) \cdot \left(\frac{\bar{m}_b}{\bar{m}_a}\right)} = \sqrt{\frac{\bar{c}_l^2 \cdot \bar{m}_b}{|\overline{OD}| \cdot \bar{F}(|\overline{OD}|)}} \tag{4}$$

Where m_a is the dimensionless mass of the arrow calculated by dividing the mass of the arrow by the *effective mass* of one limb m_b, evaluated as the mass of the limbs minus the mass of the portion of the limb connected to the riser.
Static and dynamic tests were conducted on all limbs to evaluate the quality coefficients. The static test evaluated the DFC measuring the draw force for draw lengths between the brace height and the maximum draw length at 30 in (762 mm) with 0.5 in (12.7 mm) increments. The draw force was measured using a load cell from Zemic [30] and a data acquisition (DAQ) system from HBK [31]. The draw length was measured using the Easton *Arrow Length Indicator* [32] (Figure 11) from the nock of the arrow to the button on the riser (Figure 2). The *effective draw length* was calculated by subtracting the brace height from the draw length. Figure 12 shows the DFCs evaluated for the loading and unloading of the bow, for the Winner Motive C5 limbs. The tested system (rig plus bow) did not show significant hysteresis between the loading and unloading. A reference line connecting the first and last test values was added to emphasise the non-linear nature of the DFC for an Olympic recurve bow. In the initial part of the draw where the draw force is low, the limbs are designed to accumulate potential energy at a rate greater than the corresponding linear curve. At the end of the useful draw (about 28 in), the limbs are designed to accumulate potential energy at a linear rate. The entire curve can be approximated using a third-order polynomial regression [8].



Figure 11 - Static tests rig

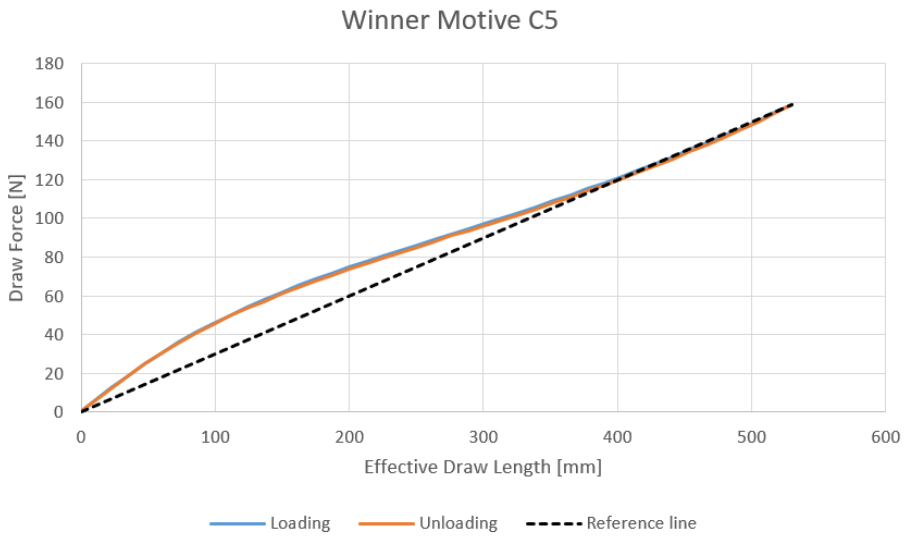


Figure 12 - Static tests: loading and unloading DFCs for the limbs Winner Motive C5

Experimental Results

The results of the static tests on the nine sets of limbs are reported in Figure 13. The DFCs are reported for the *effective draw length* evaluated by subtracting the draw length from the brace height. The DFCs are remarkably similar in shape, scaled for the increasing poundage (Table 1) from the Motive C5 on the low end, to the Axia Formula limbs at the high end. For both the NS and MXT-10 limbs, the wooden version of the limbs has a higher curve than the foam version meaning that they have higher stored potential energy. The Formula version of the Axia limbs stores more potential energy than the ILF version. The Sx+ are the only set that shows a different DFC behaviour compared to the other limbs. All data are reported in Appendix A.

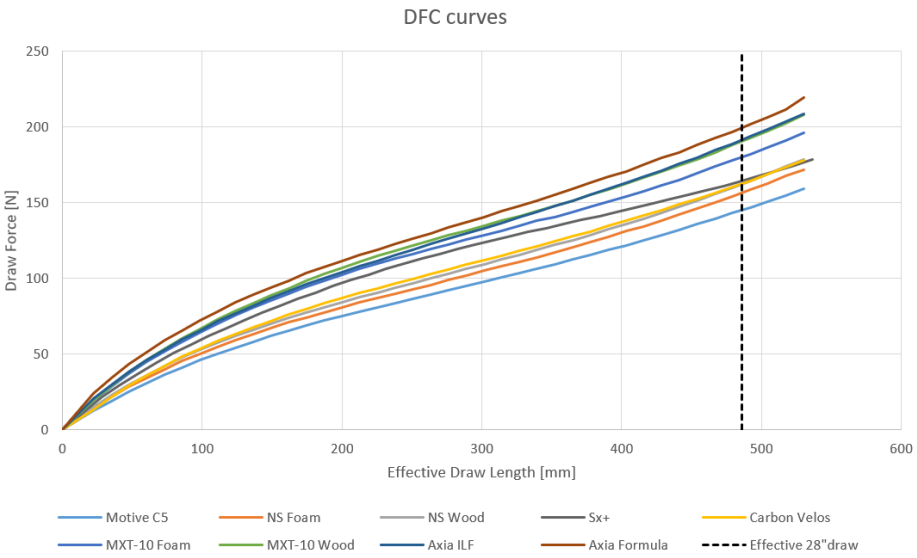


Figure 13 - Static tests: DFCs for all tested limbs

The draw force curves were normalised to eliminate the scaling effect caused by the limbs' different poundage. The *normalised draw force* was calculated by dividing the draw force by the maximum draw force, and the *normalised draw length* was calculated by dividing the effective draw length by the maximum effective draw length. The normalised draw force curves are reported in Figure 14. Figure 15 reports the same information as Figure 14 but focuses on a normalised draw length between 0.4 and 0.6. The lower curves are for the older limbs showing how the technological progress has allowed for more potential energy to be stored in the limbs. The normalised DFC for the Sx+ is different from the other curves. These limbs make use of different technology (boxed rather than laminated) in comparison with the other tested limbs and it is interesting to see the benefit of this technology in storing potential energy.

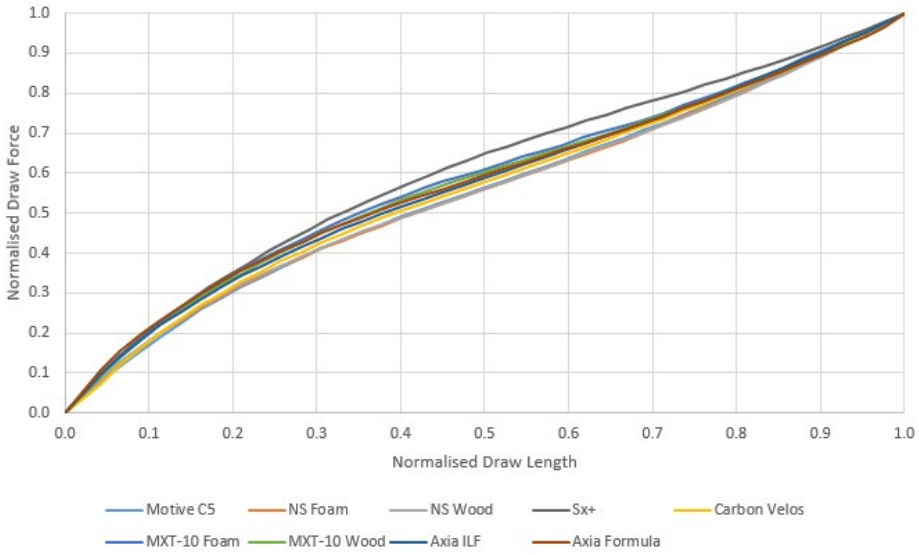


Figure 14 - Static tests: Normalised DFCs

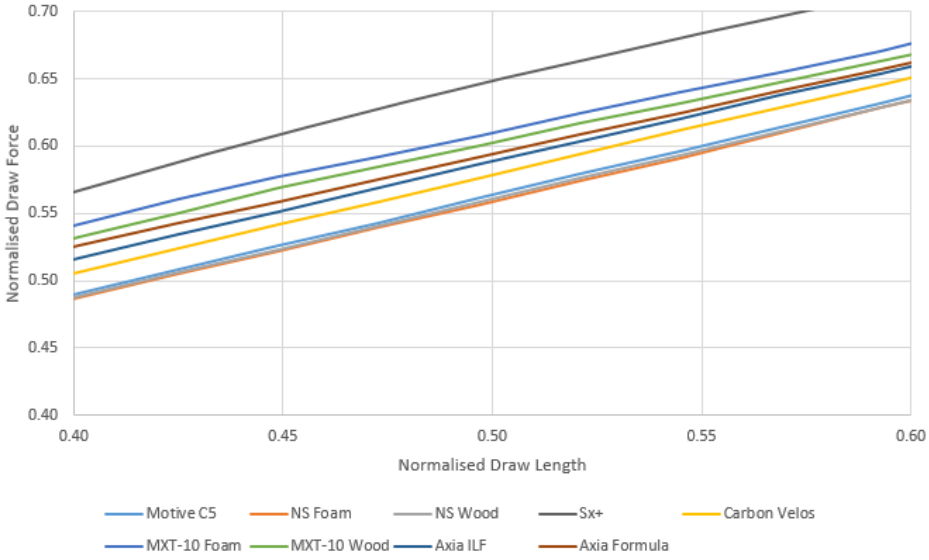


Figure 16 - Static tests: Normalised DFCs focused on the normalised draw length from 0.4 to 0.6

The smoothness of a bow can be described as the progressive variation in the draw force as the bow is drawn. In the target archery community, it is generally considered desirable to have a low differential draw force near the maximum draw length. Smoothness can be quantified by examining the slope of the DFC. If the first derivative of the DFC is plotted against draw length, a lower value of the first derivative would be interpreted as being smoother [8] than a higher value of the first derivative. A third-order polynomial curve was fitted to each measured DFC [8] allowing the first derivative of the DFC to be determined for each set of limbs. The calculated curves are reported in Figure 16 as the smoothness of the limbs. A vertical reference line at 28 in effective draw length is added for reference.

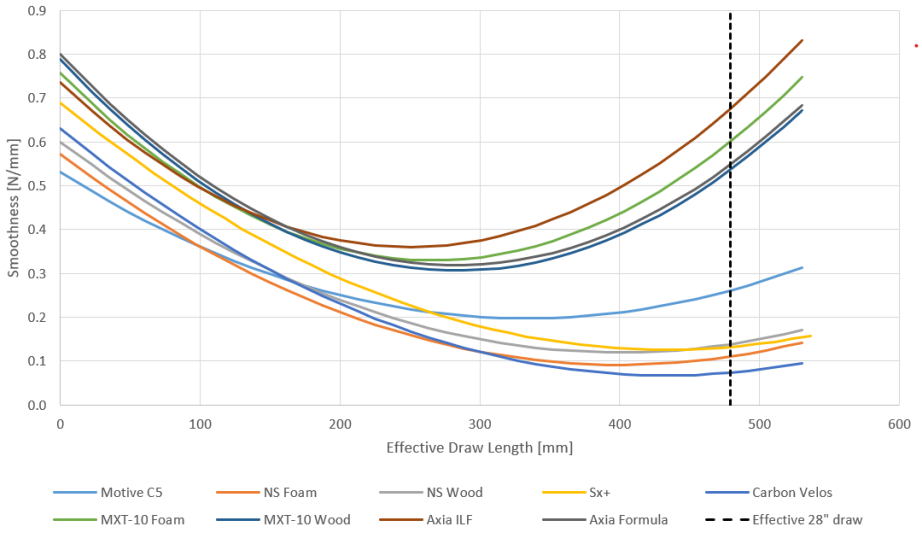


Figure 16 - Static tests: smoothness of the tested limbs

The Carbon Velos limbs are the smoothest of the tested limbs, followed by the NS Foam, the Sx+ and the NS Wood. Interestingly, the more modern limbs (Axia and MXT-10) are all less smooth than the older models.

Dynamic tests were performed to evaluate the speed of the arrow as it exited the riser (Figure 17). The limbs were divided into groups according to the nominal poundage (Table 2). One arrow per group

was shot six times for a draw length of 28 inches (711.2 mm), and the speed was measured with the use of a chronograph [33] (Table 2). For the limbs in Group 1, with nominal poundage between 30 lb and 32 lb, the Easton Avance 600 [34] was chosen as the test arrow. For the limbs in Group 2, with a nominal poundage of 36 lb, the Easton ACC 560 [35] was chosen as the test arrow. For the limbs in Group 3, with a nominal poundage between 38 lb and 40 lb, the Easton ACC 500 [35] was chosen as the test arrow.

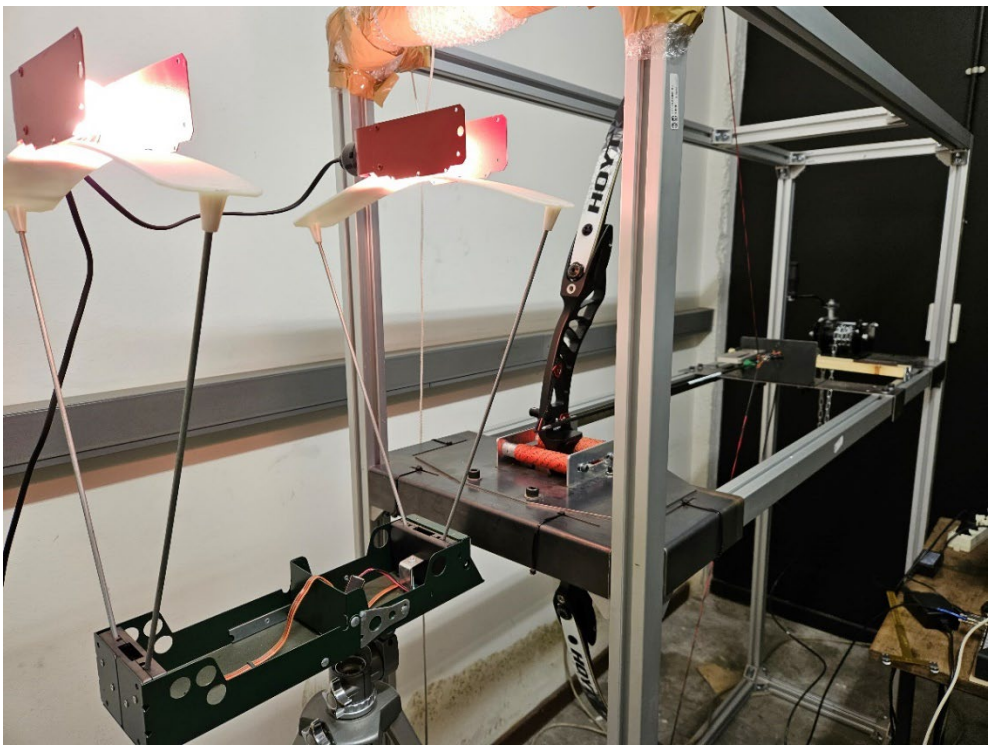


Figure 17 - The rig in the dynamic test configuration

Table 2 - Arrow selection and arrow speed for the limbs

Group Number	Limbs Name	Nominal Poundage [lb]	Arrow Name	Arrow Mass [g]	Speed of the Arrow [m/s]						Average Speed
					Arrow 1	Arrow 2	Arrow 3	Arrow 4	Arrow 5	Arrow 6	
Group 1	Motive C5	30	Easton Avance 600	20.49	46.66	46.63	46.91	46.82	46.79	46.91	46.79
	NS Foam	32			50.72	50.84	51.02	50.78	50.69	50.41	50.74
	NS Wood	32			51.33	51.24	50.93	51.21	51.27	51.11	51.18
Group 2	Sx+	36	Easton ACC 560	22.22	50.29	50.29	50.47	50.38	50.35	50.47	50.38
	Carbon Velos	36			50.78	50.72	50.57	50.60	50.38	50.54	50.60
Group 3	MXT-10 Foam	38	Easton ACC 500	23.77	51.85	51.72	51.66	51.72	51.72	51.45	51.69
	MXT-10 Wood	38			52.64	52.67	52.64	52.30	52.61	52.61	52.58
	Axia ILF	40			51.60	51.57	51.42	51.33	50.99	51.05	51.33
	Axia Formula	40			52.82	52.49	52.73	52.52	52.85	52.85	52.71

Considering the speed of the arrow, the worst performing limbs are the Motive C5, due to the inferior manufacturing technology (glass fibres instead of carbon fibres). The arrows for Group 3 are faster than the other groups even though this group used the heaviest arrow. The knowledge of the speed of the arrow allows us to evaluate the static *quality coefficient q* (Equation 1, Table 3) and the dynamic coefficients *shooting efficiency* η (Equation 3, Table 3) and *dimensionless initial velocity* ν (Equation 4, Table 4).

Table 3 – The static quality coefficient q and the dynamic quality coefficient η (shooting efficiency)

Limbs' Name	Potential Energy [Nm] @28in Draw	Effective Draw [m]	Force @28in Draw [N]	q	Kinetic Energy [Nm]	Potential Energy [Nm] @28in Draw	Shooting Efficiency η
Motive C5	40.42	0.48	142.89	0.590	22.43	38.58	0.581
NS Foam	43.58	0.48	153.88	0.591	26.38	41.60	0.634
NS Wood	45.37	0.48	159.64	0.593	26.84	43.32	0.620
Sx+	50.94	0.49	164.12	0.639	28.20	48.84	0.577
Carbon Velos	46.18	0.48	160.17	0.601	28.44	44.12	0.645
MXT-10 Foam	53.04	0.48	177.92	0.622	31.75	50.76	0.626
MXT-10 Wood	55.63	0.48	187.82	0.618	32.86	53.22	0.617
Axia ILF	55.23	0.48	188.75	0.610	31.31	52.80	0.593
Axia Formula	58.62	0.48	196.73	0.622	33.02	56.10	0.589

The static coefficient q can be interpreted as the ratio of the actual potential energy accumulated in the limbs compared to the theoretical maximum potential energy calculated as the maximum draw times the maximum force; the higher the value of q, the more efficient the limbs at storing potential energy. The limbs of Group 1 (Table 3) show a lower value of q compared to the limbs of Group 3. The possible explanation is that the limbs in Group 3 are newer than those in Group 1 and the difference is due to the advancement in both limb shape and manufacturing technology. The Sx+ has the highest q of all, due to the peculiar curvature of the limbs and their novel manufacturing technology. The results for the shooting efficiency η are quite interesting: in Group 3, Axia limbs perform worse than the MXT-10, but the MXT-10 perform worse than the NS limbs from the same manufacturer that are three years older. The best value for η is for the Carbon Velos limbs, with an efficiency of 64.5%, while the worst value for η is for the Sx+ with an efficiency of 57.7%. The limbs with a foam core have better efficiency than the limbs with a wooden core.

Table 4 - The dynamic quality coefficient ν (dimensionless initial velocity)

Limbs' Name	Upper Limb Weight [g]	Lower Limb Weight [g]	Average Limb Weight [g]	Limb Volume [mm^3]	Volume of Connection Part [mm^3]	Limb Density [g/mm^3]	Weight of Connection Part [g]	Effective limb Weight [g]	$\overline{m}_a$ [g]	m_a	ν
Motive C5	228.24	228.94	228.59	163086.26	38687.45	0.00140	54.23	174.36	10.245	0.0588	2.323
NS Foam	177.26	176.18	176.72	134210.63	31887.36	0.00132	41.99	134.73	10.245	0.0760	2.131
NS Wood	183.22	183.42	183.32	134210.63	31887.36	0.00137	43.56	139.76	10.245	0.0733	2.146
Sx+	188.14	189.84	188.99	132558.81	29002.31	0.00143	41.35	147.64	11.110	0.0752	2.141
Carbon Velos	205.77	203.64	204.71	155145.61	46042.78	0.00132	60.75	143.95	11.110	0.0772	2.154
MXT-10 Foam	183.16	184.17	183.67	152772.37	34773.04	0.00120	41.80	141.86	11.885	0.0838	2.076
MXT-10 Wood	185.97	184.89	185.43	152772.37	34773.04	0.00121	42.21	143.22	11.885	0.0830	2.060
Axia ILF	190.15	191.40	190.78	142294.77	31322.00	0.00134	41.99	148.78	11.885	0.0799	2.049
Axia Formula	207.18	209.15	208.17	156517.75	45820.13	0.00133	60.94	147.23	11.885	0.0807	2.038

The effective weight of the limb, the weight of the portion of the limb non-connected to the riser, was estimated by evaluating the volume of the limb and then evaluating the volume of the portion of the limb connected to the riser. By assuming a constant density along the limb, the weight of the effective limb was determined. The volumes of the different parts of the limb were measured using a 3D scanning technique: the limb was scanned using an Artec Eva scanner [36] and the geometry was reconstructed with Artec Studio 17 Professional [37]. Autocad Inventor Professional 2024 was used to evaluate the volumes [38]. It is accepted that the assumption of constant density is not completely accurate but this was the best estimate of the effective mass that could be obtained without cutting each limb into the two portions thereby destroying the limbs.
The dimensionless initial velocity ν is proportional to the square root of the effective mass of the limbs so, in the context of this study, the lower the value of ν, the better. Group 3 (newer limbs) have better performance than Groups 2 and 1 (older limbs) with Axia Formula limbs performing better than the ILF limbs (Table 4). In Groups 1 and 2, NS Foam performs the best and Motive C5 the worst. Carbon Velos do not show any advantage compared to ILF limbs.

Objective Metric: Mechanical Vibrations of the Bow on Shooting
As reported by Pietra et al. [21] [22], archers perceive the vibration of the bow in two different ways: airborne sound and the mechanical vibration of the riser. The sound is assumed to originate from the vibrating part of the bow, mainly the string and the limbs. The mechanical vibration of the riser is

perceived through the archer's fingers, wrist, arm, and shoulder and only a low-frequency vibration lower than 500 Hz can be perceived. It was accordingly decided to measure the mechanical vibration of the bow independently from the sound of the bow.
The vibrations associated with the shooting phase were recorded using a triaxial accelerometer from PCB Piezotronics [39] and a data acquisition (DAQ) system from National Instruments [40]. The nominal signal sampling rate was 12,000 Hz and the signal was recorded over a period of 15 s.
The three acceleration signals were captured at two different positions on the bow: Position 1 defined on the upper limb, at a distance of 200 mm from the centre of the dovetail (Figure 18); and Position 3 defined on the riser, next to the pressure button (Figure 19), close to the archer's hand.



Figure 18 - Position 1 is defined on the upper limb, at a distance of 200 mm from the centre of the dovetail

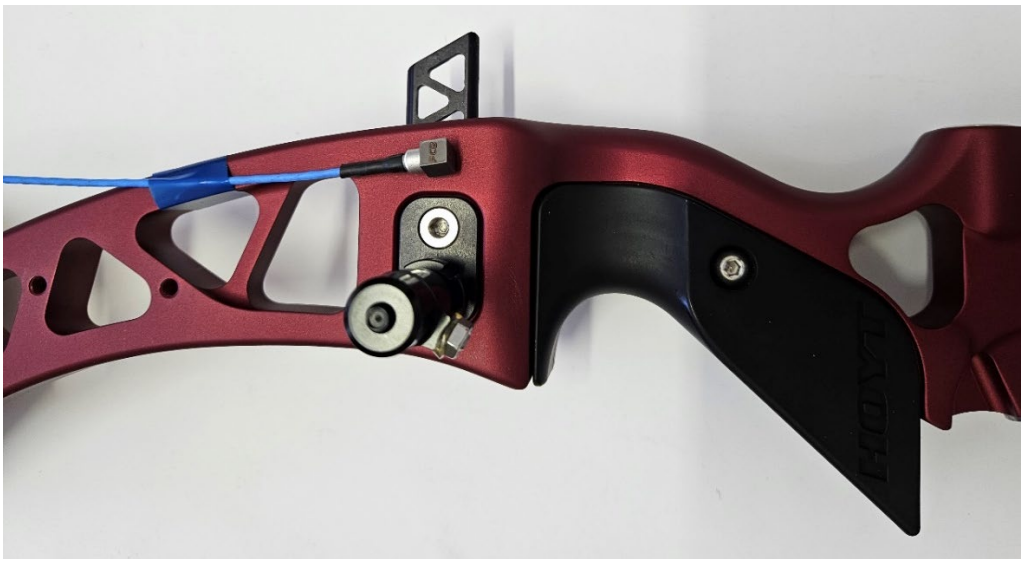


Figure 19 - Position 3 is defined on the riser, next to the pressure button

The vibration measurement procedure and signal processing methods developed in prior work of the authors [21] [22] were used. The following data statistics were calculated: the Minimum to Maximum Difference (P2P), the Root Mean Squared value (RMS) of the signal, the Damage [41] and the Decay Time. The Maximum to Minimum Difference (P2P) is a measure of the maximum amplitude of the signals, with dimension in units of g (Earth's standard gravity constant). The Root Mean Squared value (RMS) of the signal is the square root of the Mean Squared value (MSV) of the signal, also in units of g, where the MSV is defined as the average squared value of the signal over the time interval. The Damage evaluates the intensity of the vibrations acting on the human arm. The Damage was calculated by counting the peaks in the filtered data with the Rainflow method and multiplying the sorted bin edges by the number of occurrences. The Decay Time records the time necessary for the signal to reduce from the maximum amplitude to 5% of the maximum amplitude, measured in seconds. P2P, RMS, Damage, and Decay Time data were averaged across the three shots.
Because the two measuring positions have different local coordinate systems, the data were rotated into the global coordinate system defined in Figure 20. The global coordinate system is centred on the

pressure button. The X axis follows the direction of the arrow, parallel to the ground. The Y axis lies in the vertical plane of the bow (the plane created by the string and the middle section of the limbs), upward. The Z axis is perpendicular to the XY plane and to the right (as seen by the archer).

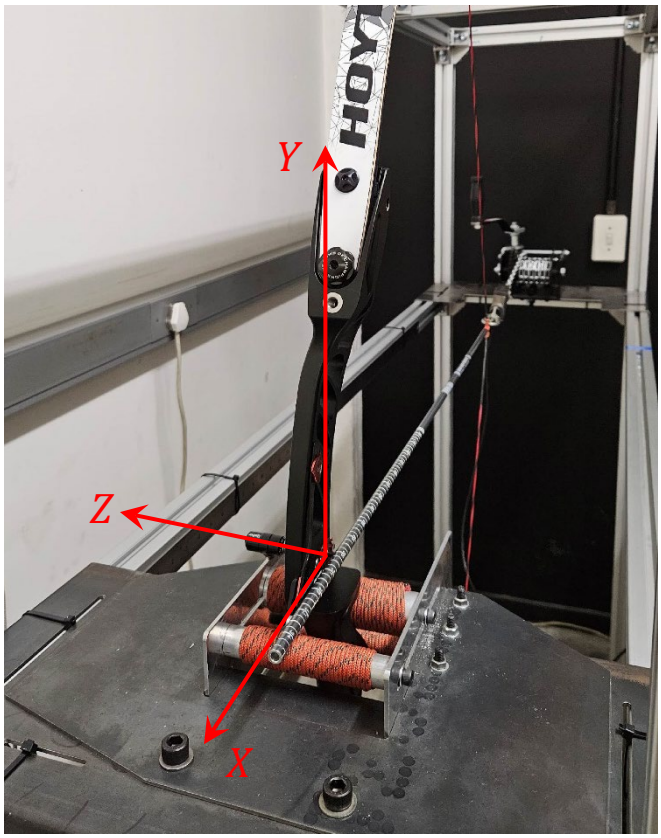


Figure 20 – Global coordinate system

The data for Position 3, which is the closest to the archer's hand, are reported in Table 5 where P2P is the root sum of squares of the P2P in the three directions X, Y and Z; and RMS is the root sum of squares of the RMS in the three directions X, Y and Z. To consider the effect of the different poundages of the limbs, the data were converted into the units of $^{m}/_{s^2}$ and scaled using the *maximum energy* (Max E) defined as $|\overline{OD}| \cdot \bar{F}(|\overline{OD}|)$ where $|\overline{OD}|$ is equal to 28" draw (711.2 mm) and $\bar{F}(|\overline{OD}|)$ is the measured draw force for each set of limbs. The scaled data are reported in Table 6. The corresponding data for Position 1 are reported in Appendix B.

Table 5 - Mechanical vibration data for Position 3

Limbs' Name	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS	Decay Time [s]
	[g]								
Motive C5	386.50	109.90	172.89	437.43	24.71	4.36	12.05	27.84	0.1882
NS Foam	506.65	146.79	222.90	572.64	29.12	6.35	12.44	32.30	0.1429
NS Wood	537.99	210.31	334.79	667.64	29.22	8.10	16.39	34.47	0.0946
SX+	324.84	115.22	231.67	415.29	24.93	5.51	16.47	30.38	0.1691
Carbon Velos	424.58	105.58	277.97	518.35	27.64	6.03	17.52	33.28	0.1254
MXT-10 Foam	451.86	120.82	303.19	557.41	31.97	5.50	13.61	35.18	0.1492
MXT-10 Wood	494.15	120.02	232.40	559.10	34.73	5.69	15.23	38.35	0.1391
Axia ILF	449.68	84.62	210.59	503.71	28.71	4.63	13.38	32.01	0.1535
Axia Formula	472.74	99.17	242.12	540.32	31.48	5.90	14.36	35.10	0.1271

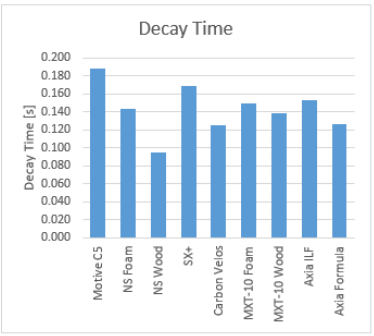
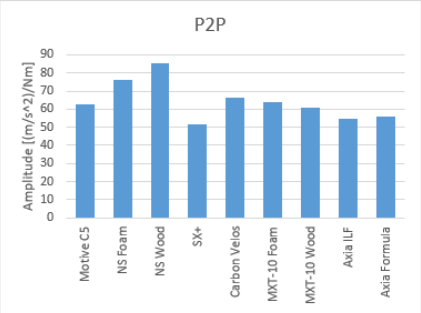
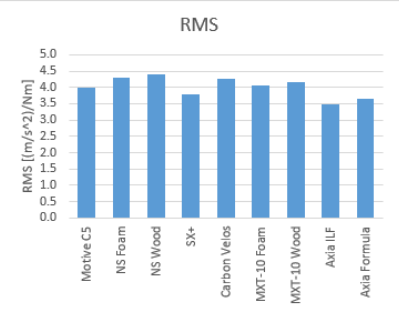


Table 6 - Mechanical vibration data for Position 3, scaled with the maximum energy

Limbs' Name	Max E [Nm] @ 28in draw	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS
					[(m/s^2) / Nm]				
Motive C5	68.50	55.35	15.74	24.76	62.64	3.54	0.62	1.73	3.99
NS Foam	73.77	67.37	19.52	29.64	76.15	3.87	0.84	1.65	4.29
NS Wood	76.53	68.96	26.96	42.91	85.58	3.75	1.04	2.10	4.42
Sx+	78.68	40.50	14.37	28.89	51.78	3.11	0.69	2.05	3.79
Carbon Velos	76.79	54.24	13.49	35.51	66.22	3.53	0.77	2.24	4.25
MXT-10 Foam	85.29	51.97	13.90	34.87	64.11	3.68	0.63	1.57	4.05
MXT-10 Wood	90.04	53.84	13.08	25.32	60.91	3.78	0.62	1.66	4.18
Axia ILF	90.49	48.75	9.17	22.83	54.61	3.11	0.50	1.45	3.47
Axia Formula	94.31	49.17	10.32	25.18	56.20	3.27	0.61	1.49	3.65





The analysis of the Decay Time (Table 5) shows that the Motive C5 are the limbs that vibrate for the longest period, followed by the Sx+, highlighting the effect of the manufacturing technology on the vibration damping of the limbs. Wood core has a superior damping capability compared to the foam core as reported in the literature [8], while newer limbs do not perform better than older limbs. Data analysis for the mechanical vibrations (P2P and RMS, Table 6), shows a general trend in the reduction of the amplitude of the vibration with the newer limbs with the Sx+ being the best of the tested limbs from the P2P point of view.

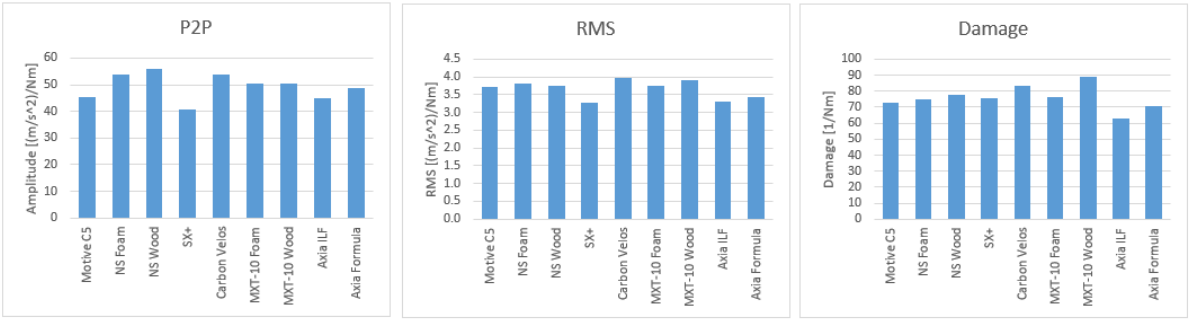
The mechanical vibration data were filtered with a lowpass filter at 500 Hz to account for the human physiology in perceiving vibrations through the upper arms [42] [43] (Table 7), and then scaled using the maximum energy in the bow (Table 8). Damage is the root sum of squares of the Damages in the three directions X, Y and Z. The corresponding data for Position 1 are reported in Appendix B.

Table 7 - Mechanical vibration data for Position 3, filtered with a lowpass filter at 500 Hz

Limbs' Name	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS	Damage X	Damage Y	Damage Z	Damage
				[g]								
Motive C5	294.20	26.24	111.86	315.84	23.47	2.09	10.80	25.92	4102.5	520.0	2776.7	4981.0
NS Foam	392.60	43.24	93.39	405.87	26.87	3.29	9.21	28.59	4935.0	696.0	2444.2	5550.9
NS Wood	400.69	35.75	165.77	435.09	26.18	2.94	12.59	29.20	4842.5	755.3	3402.5	5966.3
SX+	283.61	40.19	158.39	327.32	22.05	3.06	13.95	26.27	4067.5	733.8	4287.5	5955.3
Carbon Velos	368.88	58.50	196.07	421.83	26.25	4.53	15.93	31.04	4815.0	994.2	4121.7	6415.7
MXT-10 Foam	409.15	44.35	147.52	437.18	30.69	2.76	10.93	32.70	5830.0	610.0	2850.0	6517.9
MXT-10 Wood	438.38	43.15	148.32	464.80	33.45	3.04	13.08	36.04	6562.5	776.5	4548.3	8022.3
Axia ILF	374.58	37.58	172.79	414.22	27.84	2.97	11.86	30.40	4830.0	657.3	2901.7	5672.8
Axia Formula	425.65	65.40	181.99	467.52	30.32	4.54	12.03	32.94	5904.2	939.2	2950.8	6667.0

Table 8 - Mechanical vibration data for Position 3, filtered with a lowpass filter at 500 Hz. The reported data are scaled with the maximum energy

Limbs' Name	Max E [Nm] @ 28in draw	P2P - X	P2P - Y	P2P - Z	P2P [(m/s^2) / Nm]	RMS - X	RMS - Y	RMS - Z	RMS	Damage X	Damage Y [1 / Nm]	Damage Z	Damage
Motive C5	68.501	42.13	3.76	16.02	45.23	3.36	0.30	1.55	3.71	59.9	7.6	40.5	72.7
NS Foam	73.770	52.21	5.75	12.42	53.97	3.57	0.44	1.22	3.80	66.9	9.4	33.1	75.2
NS Wood	76.531	51.36	4.58	21.25	55.77	3.36	0.38	1.61	3.74	63.3	9.9	44.5	78.0
Sx+	78.679	35.36	5.01	19.75	40.81	2.75	0.38	1.74	3.28	51.7	9.3	54.5	75.7
Carbon Velos	76.785	47.13	7.47	25.05	53.89	3.35	0.58	2.04	3.97	62.7	12.9	53.7	83.6
MXT-10 Foam	85.295	47.06	5.10	16.97	50.28	3.53	0.32	1.26	3.76	68.4	7.2	33.4	76.4
MXT-10 Wood	90.041	47.76	4.70	16.16	50.64	3.64	0.33	1.42	3.93	72.9	8.6	50.5	89.1
Axia ILF	90.487	40.61	4.07	18.73	44.91	3.02	0.32	1.29	3.30	53.4	7.3	32.1	62.7
Axia Formula	94.312	44.27	6.80	18.93	48.63	3.15	0.47	1.25	3.43	62.6	10.0	31.3	70.7



The analysis of the amplitude of the filtered accelerations (P2P, Table 8) shows interesting results: newer limbs vibrate less than older limbs (MXT compared to NS, Axia compared to Carbon Velos), wood core and foam core perform the same (MXT), Motive C5 has the same level of filtered vibrations as the more expensive Axia. The Sx+ has the lowest level of filtered vibrations. Axia Formula limbs perform slightly worse than the Axia ILF, Carbon Velos limbs perform slightly better compared to NS ILF limbs. The RMS analysis (energy content of the filtered vibration signal) shows Sx+ and Axia limbs perform better than all other limbs. Motive C5, NS and MXT show the same level of energy in the vibration signal, better than the Carbon Velos. Wood limbs perform better than foam for the NS limbs, but worse for the MXT limbs. Damage analysis shows better performance of the Axia ILF compared to all other limbs. The MXT foam has the same level of Damage as the Motive C5, NS and Sx+, while the MXT wood shows the highest level of Damage.

Objective Metric: Intensity of the Noise of the Bow on Shooting

The sound emitted by the bow on shooting was recorded using the GRAS 40PH-10 CCP Free-field Array Microphone [44] and a data acquisition (DAQ) system from National Instruments [40]. Three shots were recorded for each set of limbs and the recordings were trimmed to 0.5 s around the release (event duration). The measurements were recorded outdoors at the Archers of the Zoo Lake Club range (Johannesburg, South Africa) early in the morning to avoid other sources of sound.

The three test shots for the Axia ILF are shown in Figure 21, while the three shots for the Axia Formula are shown in Figure 22. As reported in the figures, the measurements of the sound of the bow on shooting are fairly repeatable and distinctive for the tested set of limbs.

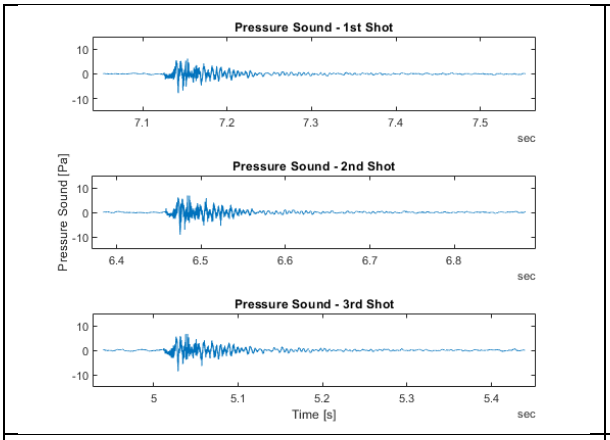


Figure 21 – Sound pressure measurements for the limbs Axia ILF

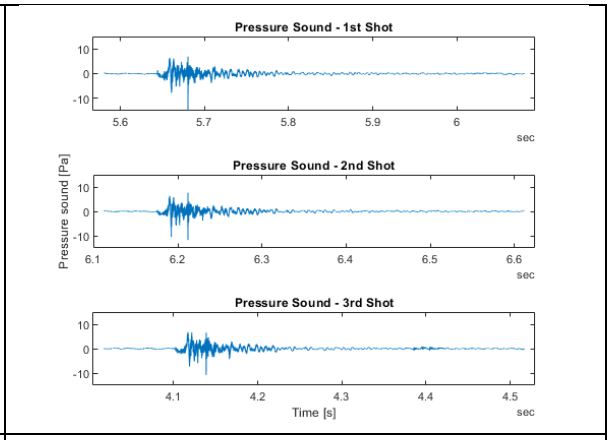


Figure 22 - Sound pressure measurements for the limbs Axia Formula

The sound signal was filtered with an A-weighted filter to account for the different sensitivity of the microphone compared to the human ear. The A-weighted filter is a bandpass filter designed to simulate the perceived loudness of low-level tones to a human listener. The filter progressively de-emphasizes frequencies below 500 Hz [45] as illustrated in Figure 23. The filter characteristics roughly represent the inverse of the hearing level curve with 30 dB at 1 kHz. The A-weighting function is standardized in EN 60651 [46]. The effect of the A-weighting filter on the sound signal is shown in Figure 24 for the time domain, and in Figure 25 for the frequency domain.

The *Maximum Sound Pressure Level* (Max SPL) and the *Equivalent Continuous Sound Level* (L_{eq}) were subsequently calculated. The SPL was calculated using the *Sound Pressure Level Calculator* by Greene [47] considering a reference time equal to 0.5 s. The L_{eq} value was calculated using the equation provided in the MathWorks documentation [45]:

$$L_{eq} = 10 \cdot \log_{10}\left[\frac{\left(\frac{1}{T}\right)\int_{t_1}^{t_2} y^2 dt}{p_0^2}\right] = 20 \cdot \log_{10}\left[\frac{RMS(y)}{p_0}\right] \quad (5)$$

where y is the output of the frequency-weighted filter, p_0 is the reference sound pressure ($p_0 = 20 \cdot 10^{-6}\ N/m^2$) and RMS is the root mean squared value of the filtered signal [45]. To account for the different poundage of the tested limbs, the equivalent continuous sound level L_{eq} was divided by the nominal poundage of the corresponding set of limbs. The data are reported in Table 9.

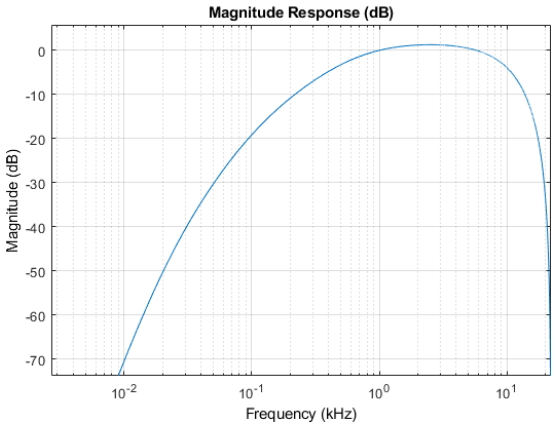


Figure 23 - A-Weighting filter [45]

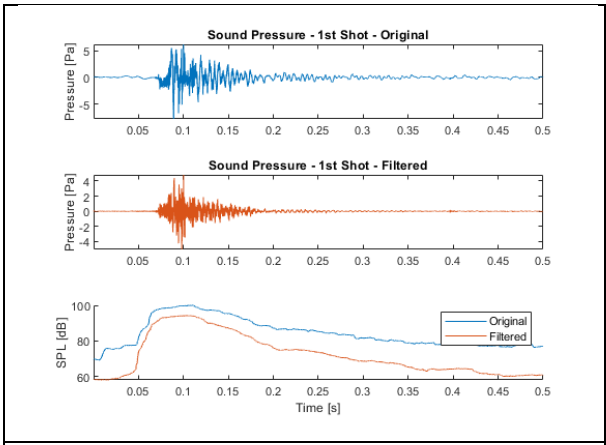


Figure 24 - Axia ILF - 1st shot signal filtered with an A-weighted filter. Time domain

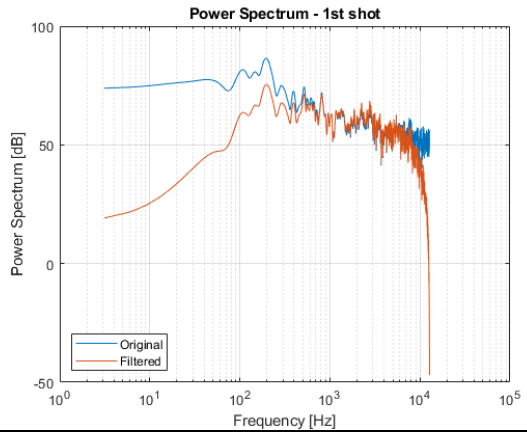


Figure 25 - Axia ILF - 1st shot signal filtered with an A-weighted filter. Frequency domain

Table 9 - Sound analysis results for the tested limbs

	Max Peak [dB]	SPL [dB]	Leq	Poundage [lb]	Poundage [N]	Leq/Poundage [1/N]
Motive C5	93.53	84.24	84.24	30	133.45	0.631
NS Foam	97.27	87.59	87.59	32	142.34	0.615
NS Wood	102.31	92.51	92.51	32	142.34	0.650
SX+	96.39	87.17	87.17	36	160.14	0.544
Carbon Velos	96.84	87.28	87.28	36	160.14	0.545
MXT-10 Foam	96.55	87.49	87.49	38	169.03	0.518
MXT-10 Wood	96.81	87.62	87.62	38	169.03	0.518
Axia ILF	95.14	85.92	85.92	40	177.93	0.483
Axia Formula	95.64	86.19	86.19	40	177.93	0.484

The data analysis for the $L_{eq}/Poundage$ column shows that modern limbs (Axia and MXT-10) radiate less sound on shooting compared to older limbs (NS and Motive C5), with the Axia quieter than the MXT. Formula and ILF limbs radiate the same level of sound, NS wooden core are noisier than NS foam core while MXT limbs radiate the same level of sound whether they have wooden or foam cores.

Subjective Metrics: Perceived Sensations on Shooting

A questionnaire was prepared and administered to ten archers from Archers of the Zoo Lake Club, Johannesburg, South Africa. All participants were of the Intermediate Level (proficiency evaluations based on the Archers of the Zoo Lake Club guidelines [48]) and equally divided into recurve and barebow archers [49]. The questionnaire asked about the physical sensations of shooting with a particular set of limbs mounted on the riser. The limbs were divided into three groups to avoid bias in testing the limbs due to the different poundage:

- Group 1: Motive C5, NS Wood and Foam. Nominal poundage between 30 and 32 pounds.
- Group 2: Sx+ and Carbon Velos. Nominal poundage 36 pounds.
- Group 3: MXT-10 Wood and Foam, Axia ILF and Formula. Nominal poundage between 38 and 40 pounds.

Each archer confirmed in writing that they were willing to participate in the study and agreed to their data being used in this paper. All archers agreed to shoot all sets of limbs. The tests were organised for the same archer to shoot all limbs on the same day, moving from the limbs in Group 1 to Group 3. The order of the testing of the limbs was kept constant between archers. The archers were generally unaware of the manufacturing technology they were testing, while ILF and Formula limbs were easily recognisable.

The questionnaire was divided into six questions:

1. The perceived *stiffness* of the tested limbs at the beginning, in the middle and at the end of the drawing phase. The stiffness was defined as the measure of the amount of force necessary

to pull the string into the specified position. The perceived stiffness was evaluated using a Likert scale ranging from 1 “very stiff” to 5 “very soft”.

2. The perceived *smoothness* of the tested limbs at the beginning, in the middle and at the end of the drawing phase. The smoothness was defined as the perception of the change in the increment of force during the drawing phase, necessary to create a corresponding increment of draw. The perceived smoothness was evaluated by asking if the archer perceived any change in the smoothness and, if a change was perceived, to evaluate the change qualitatively.
3. The perceived *speed of the limbs*, was defined as a measurement of how quickly the limbs react when the string is released. The perceived speed was evaluated using a Likert scale ranging from 1 “very quick” to 5 “very slow”.
4. The *mechanical vibrations* of the limbs as perceived through the archer’s hand. The perceived mechanical vibrations were evaluated using a Likert scale ranging from 1 “very high” to 5 “very low”.
5. The perceived *sound intensity* of the bow on shooting. The perceived sound of the bow was evaluated using a Likert scale ranging from 1 “very noisy” to 5 “very quiet”.
6. The limb *preference* within the group. The preference within a group was necessary to avoid any bias between heavy and light poundage limbs.

It is assumed that a five-point Likert scale is sensitive enough to capture the archers’ experiences in shooting the tested limbs. Furthermore, it is assumed that the scale is equally spaced between the five steps. This assumption is necessary to calculate the correlations between subjective and objective metrics and to answer the research questions but it is an approximation of a more complex reality.
In the creation of the questionnaire, it was necessary to differentiate between stiffness and smoothness to avoid archers reporting the wrong perception during the tests. Table 10 reports the mode and median for some of the collected data, where the mode is the most common number that appears in the set of data, and the median is the middle value of a set of data [25]. All results and the mathematical analysis to convert the questionnaire responses to the data reported in Table 10 are detailed in Appendix C.

Table 10 - Results from the questionnaire

	Stiffness - Mode of the Results			Average		Summary of the Perceived Smoothness			Average
	Beginning	Middle	End	Stiffness		Beginning	Middle	End	Smoothness
Motive C5	2	2	2	2.00		0	0	-0.1	-0.05
NS Foam	4	4	4	4.00		0	0	-0.1	-0.05
NS Wood	3	3	1	2.00		0.1	0	-0.4	-0.18
Sx+	3	3	4	3.50		0	0	0.1	0.05
Carbon Velos	3	3	3	3.00	Very Stiff [1]	0.1	0	-0.4	-0.18
MXT-10 Foam	4	3	3	3.25	Stiff [2]	0	0	0.1	0.05
MXT-10 Wood	2	2	2	2.00	Normal [3]	0	-0.1	-0.1	-0.08
Axia ILF	3	3	3	3.00	Soft [4]	-0.1	0	0	-0.03
Axia Formula	2	3	2	2.25	Very Soft [5]	0	0	-0.4	-0.20

	Speed of the Limbs			Mechanical Vibrations			Sound			Absolute
	Mode	Median		Mode	Median		Mode	Median		Preference
Motive C5	4.0	4.0		3.00	2.50		3.00	3.00		2.4
NS Foam	3.0	2.5		3.00	3.00		4.00	3.00		1.0
NS Wood	2.0	2.0		3.00	2.50		1.00	2.00		2.6
Sx+	3.0	2.5		4.00	3.50		4.00	3.00		1.3
Carbon Velos	2.0	2.0	Very Quick [1]	3.00	3.00	Very High [1]	4.00	4.00	Very Noisy [1]	1.7
MXT-10 Foam	2.0	2.0	Quick [2]	4.00	4.00	High [2]	4.00	4.00	Noisy [2]	1.1
MXT-10 Wood	1.0	1.5	Normal [3]	2.00	2.00	Normal [3]	2.00	2.50	Normal [3]	3.9
Axia ILF	2.0	2.0	Slow [4]	3.00	3.00	Low [4]	3.00	3.00	Quiet [4]	2.8
Axia Formula	2.0	2.0	Very Slow [5]	3.00	3.00	Very Low [5]	3.00	3.00	Very Quiet [5]	2.2

Correlations Between Objective and Subjective Metrics

The correlation between objective and subjective metrics was studied by evaluating the Pearson correlation coefficient r and the coefficient of determination $V = r^2$ [25]. A Pearson correlation coefficient of $r > 0.5$ indicates a direct correlation, while $r < -0.5$ indicates an inverse correlation, while a coefficient of determination of $V > 0.25$ indicates a strong relationship, $0.09 < V < 0.25$ indicates a moderate relationship and $V < 0.09$ indicates a weak relationship [25]. Considering all 38 metrics defined in this work resulted in a large correlation matrix. The parts of the correlation matrix

that give an insight into the problem are reported in Appendix D. Table 11 reports significant correlation results between experimental and perceived metrics. A good correlation was found between the experimental average stiffness of the limbs (Appendix D) and the perceived average stiffness, while no correlation was found between the experimental average smoothness (Appendix D) and the perceived average smoothness, meaning that the archers perceive the string stiffness more clearly than the smoothness of the limbs. A moderate correlation was found between the filtered vibrations at Position 3 compared to the perceived vibration of the bow, as reported by Pietra et al. in previous works [21] [22]. The filtered acceleration at Position 3 scaled for the maximum energy showed a lower level of correlation with the perceived vibrations (Appendix D). The suggested explanation is that the archers evaluate the level of vibrations irrespective of the poundage of the limbs. No correlation was found between the perceived vibrations and the mechanical vibration measured at Position 1, and the perceived sound and the mechanical vibration measured at Position 1 (Appendix D). The archer does not perceive the vibrations from Position 1 (limbs). The perceived sound showed a good correlation with the experimental sound metrics (max peak and SPL) and no significant correlation with $L_{eq}/Poundage$ (Table 11). The proposed explanation is that the archers evaluate the sound of the bow on shooting on an absolute scale, without adjusting for the poundage of the limbs. The experimental speed was strongly inversely correlated to the perceived speed of the arrows (Table 11). The archers perceive the speed of the arrows with astonishing precision, considering that the difference between the slowest and the fastest arrows is $5.92\ m/s$ (Table 2), or about 8% of the average speed. The inverse correlation is due to the scoring scale decided for the subjective metric. The decay time in Position 1 was strongly correlated to the acceleration metrics in Position 1 and to the experimental and perceived speed of the arrow. Also, the decay time in Position 3 was strongly correlated to the acceleration metrics in Position 3 and to the experimental and perceived speed of the arrow (Table 11). These findings are in contrast with the results from previous analyses [21] [22]. The suggested explanation is that in the previous works, the bow was unchanged during the tests. The decay time is a characteristic principally related to the limbs, marginally related to the barebow stabilisation system used in the previous tests [21], or the amount of damping previously introduced in the bow [22].

Table 11 - Selected correlation results between experimental and perceived metrics

	Experimental Average Stiffness	Perceived Average Stiffness
Motive C5	0.8337	2.00
NS Foam	0.8419	4.00
NS Wood	0.8747	2.00
Sx+	0.8350	3.50
Carbon Velos	0.7866	3.00
MXT-10 Foam	0.8416	3.25
MXT-10 Wood	0.8859	2.00
Axia ILF	0.8389	3.00
Axia Formula	0.8819	2.25
r		-0.51
$V = r^2$		0.2556

	Experimental Average Smoothness	Perceived Average Smoothness
Motive C5	0.0019	-0.05
NS Foam	0.0011	-0.05
NS Wood	0.0013	-0.18
Sx+	0.0012	0.05
Carbon Velos	0.0009	-0.18
MXT-10 Foam	0.0029	0.05
MXT-10 Wood	0.0027	-0.08
Axia ILF	0.0030	-0.03
Axia Formula	0.0026	-0.20
r		0.24
$V = r^2$		0.0569

	Position 3 filter at 500 Hz			
	Vibrations Mode	P2P	RMS	Damage
Motive C5	3.0	315.84	25.92	4981
NS Foam	3.0	405.87	28.59	5551
NS Wood	3.0	435.09	29.20	5966
Sx+	4.0	327.32	26.27	5955
Carbon Velos	3.0	421.83	31.04	6416
MXT-10 Foam	4.0	437.18	32.70	6518
MXT-10 Wood	2.0	464.80	36.04	8022
Axia ILF	3.0	414.22	30.40	5673
Axia Formula	3.0	467.52	32.94	6667
r		-0.42	-0.47	-0.42
$V = r^2$		0.1786	0.2220	0.1758

	Sound Mode	Max peak [dB]	SPL [dB]	Leq/Poundage [1/N]
Motive C5	3.0	93.53	84.24	0.631
NS Foam	4.0	97.27	87.59	0.615
NS Wood	1.0	102.31	92.51	0.650
Sx+	4.0	96.39	87.17	0.544
Carbon Velos	4.0	96.84	87.28	0.545
MXT-10 Foam	4.0	96.55	87.49	0.518
MXT-10 Wood	2.0	96.81	87.62	0.518
Axia ILF	3.0	95.14	85.92	0.483
Axia Formula	3.0	95.64	86.19	0.484
r	-0.55	-0.55	-0.28	
$V = r^2$	0.3046	0.3072	0.0802	

	Speed [m/s]	Speed Mode
Motive C5	46.8	4.0
NS Foam	50.7	3.0
NS Wood	51.2	2.0
Sx+	50.4	3.0
Carbon Velos	50.6	2.0
MXT-10 Foam	51.7	2.0
MXT-10 Wood	52.6	1.0
Axia ILF	51.3	2.0
Axia Formula	52.7	2.0
r		-0.87
$V = r^2$		0.7634

	Position 1 Decay Time [s]	Position 1 P2P	Position 1 RMS	Position 1 filter at 500 Hz P2P	Position 1 filter at 500 Hz RMS	Position 1 filter at 500 Hz Damage	Speed Mode	Speed [m/s]
Motive C5	0.1719	2102.50	148.20	1552.57	140.45	24464.13	4.0	46.8
NS Foam	0.0858	2659.51	173.11	2130.54	155.63	34376.24	3.0	50.7
NS Wood	0.0991	2578.46	171.16	1816.33	148.52	29663.52	2.0	51.2
Sx+	0.0919	2540.91	173.53	1995.75	155.70	29382.12	3.0	50.4
Carbon Velos	0.0915	2421.94	157.07	1988.09	144.69	28336.69	2.0	50.6
MXT-10 Foam	0.1000	2750.79	171.56	1796.41	148.97	28702.69	2.0	51.7
MXT-10 Wood	0.0896	2721.04	172.14	1839.33	147.30	27099.79	1.0	52.6
Axia ILF	0.1207	2670.63	157.24	1734.59	142.99	28784.18	2.0	51.3
Axia Formula	0.0975	2640.09	154.50	1995.53	137.57	25475.92	2.0	52.7
r	-0.76	-0.71	-0.84	-0.52	-0.58	0.62	-0.80	
$V = r^2$	0.5815	0.4995	0.7033	0.2745	0.3314	0.3865	0.6375	

	Position 3 Decay Time [s]	Position 3 P2P	Position 3 RMS	Position 3 [(m/s^2) / Nm] P2P	Position 3 [(m/s^2) / Nm] RMS	Position 3 filter at 500 Hz P2P	Position 3 filter at 500 Hz RMS	Position 3 filter at 500 Hz Damage	Speed Mode	Speed [m/s]
Motive C5	0.1882	437.43	27.84	62.64	3.99	315.84	25.92	4981.04	4.0	46.8
NS Foam	0.1429	572.64	32.30	76.15	4.29	405.87	28.59	5550.91	3.0	50.7
NS Wood	0.0946	667.64	34.47	85.58	4.42	435.09	29.20	5966.34	2.0	51.2
Sx+	0.1691	415.29	30.38	51.78	3.79	327.32	26.27	5955.30	3.0	50.4
Carbon Velos	0.1254	518.35	33.28	66.22	4.25	421.83	31.04	6415.66	2.0	50.6
MXT-10 Foam	0.1492	557.41	35.18	64.11	4.05	437.18	32.70	6517.94	2.0	51.7
MXT-10 Wood	0.1391	559.10	38.35	60.91	4.18	464.80	36.04	8022.26	1.0	52.6
Axia ILF	0.1535	503.71	32.01	54.61	3.47	414.22	30.40	5672.79	2.0	51.3
Axia Formula	0.1271	540.32	35.10	56.20	3.65	467.52	32.94	6666.98	2.0	52.7
r	-0.87	-0.65	-0.62	-0.46	-0.75	-0.44	-0.39	0.64	-0.62	
$V = r^2$	0.7541	0.4272	0.3791	0.2099	0.5617	0.1952	0.1498	0.4119	0.3884	

To understand how the archers rated the tested limbs, a correlation analysis was developed between the absolute preference, the experimental metrics and the perceived metrics. Table 12 reports significant correlation results. All data are reported in Appendix D.

Table 12 - Selected correlations between the absolute preference and experimental metrics

	Absolute Preference	Avg. Stiffness	Position 1 [(m/s^2) / Nm] P2P	Position 1 [(m/s^2) / Nm] RMS	Position 1 filter at 500 Hz P2P	Position 1 filter at 500 Hz RMS	Position 1 filter at 500 Hz Damage	Position 1 filter at 500 Hz [(m/s^2) / Nm] P2P	Position 1 filter at 500 Hz [(m/s^2) / Nm] RMS	Position 1 filter at 500 Hz [(m/s^2) / Nm] Damage	Position 3 filter at 500 Hz P2P	Position 3 filter at 500 Hz RMS	Position 3 filter at 500 Hz Damage	Average Stiffness	Average Smoothness	Vibrations Mode	Speed Mode
Motive C5	2.4	0.8337	301.10	21.22	1552.57	140.45	24464	222.34	20.11	357	315.84	25.92	4981	2.00	-0.05	3.0	4.0
NS Foam	1.0	0.8419	353.66	23.02	2130.54	155.63	34376	283.32	20.70	466	405.87	28.59	5551	4.00	-0.05	3.0	3.0
NS Wood	2.6	0.8747	330.51	21.94	1816.33	148.52	29664	232.82	19.04	388	435.09	29.20	5966	2.00	-0.18	3.0	2.0
Sx+	1.3	0.8350	316.81	21.64	1995.75	155.70	29382	248.84	19.41	373	327.32	26.27	5955	3.50	0.05	4.0	3.0
Carbon Velos	1.7	0.7866	309.42	20.07	1988.09	144.69	28337	254.00	18.49	369	421.83	31.04	6416	3.00	-0.18	3.0	2.0
MXT-10 Foam	1.1	0.8416	316.38	19.73	1796.41	148.97	28703	206.61	17.13	337	437.18	32.70	6518	3.25	0.05	4.0	2.0
MXT-10 Wood	3.9	0.8859	296.46	18.75	1839.33	147.30	27100	200.40	16.05	301	464.80	36.04	8022	2.00	-0.08	2.0	1.0
Axia ILF	2.8	0.8389	289.53	17.05	1734.59	142.99	28784	188.05	15.50	318	414.22	30.40	5673	3.00	-0.03	3.0	2.0
Axia Formula	2.2	0.8819	274.61	16.07	1995.53	137.57	25476	207.57	14.31	270	467.52	32.94	6667	2.25	-0.20	3.0	2.0
r	0.53	-0.54	-0.44	-0.47	-0.47	-0.49	-0.63	-0.47	-0.56	0.32	0.45	0.46	-0.79	-0.33	-0.80	-0.48	
$V = r^2$	0.2798	0.2883	0.1978	0.2248	0.2188	0.2449	0.4004	0.2234	0.3118	0.1019	0.2068	0.2095	0.6172	0.1083	0.6368	0.2308	

The absolute preference is correlated to the experimental average stiffness: the greater the limb stiffness, the lower the liking of the limbs (in the absolute preference, the lower the reported value, the higher the preference). The absolute preference is also inversely correlated to the mechanical vibrations from Positions 1 both scaled data, filtered data and filtered-scaled data. The absolute preference is moderately directly correlated to the mechanical vibrations from Positions 3 (filtered data). If the direct correlation with the mechanical vibrations in Position 3 is an expected result (the lower the vibrations, the higher the preference) the inverse correlation for the mechanical vibrations in Position 1 is unexpected. The archer is generally not aware of the vibrations in Position 1 and the inverse correlation means that the higher the vibrations, the higher the liking of the limbs. Also, there is a strong inverse correlation between the absolute preference, the perceived average stiffness, and the perceived vibrations. The proposed explanation is that the limbs were tested from the low to the high poundage so the archers expected a progressively higher level of vibrations. Also, changing the limbs from one test to the other did not allow the archers to create a reference vibration level. The two effects together created a situation where the level of vibrations in the bow was not part of the decision about the liking of the limbs and the choice of the limbs of preference was more based on a personal perception of stiffness and vibration level than on measurable quantities. Interestingly enough, no correlations are found with decay times or sound metrics meaning that the time-to-rest of the limbs and the sound of the bow are not important in the liking of the limbs. No correlation is found with the perceived smoothness, meaning that one of the limbs' marketing points is not important for the liking of the limbs.

Table 13 reports significant correlation results between the quality coefficients and the experimental metrics. All data are reported in Appendix D.

Table 13 - Selected correlations between the static quality coefficient q, the shooting efficiency η, the dimensionless initial velocity v, and experimental metrics

	Quality Coefficient q	Position 3 [(m/s^2) / Nm] P2P	Position 3 [(m/s^2) / Nm] RMS	Position 3 Filter at 500 Hz [(m/s^2) / Nm] P2P	Position 3 Filter at 500 Hz [(m/s^2) / Nm] RMS	Damage	Leq/Poundage [1/N]
Motive C5	0.5488	62.64	3.99	45.23	3.71	73	0.631
NS Foam	0.5478	76.15	4.29	53.97	3.80	75	0.615
NS Wood	0.5483	85.58	4.42	55.77	3.74	78	0.650
Sx+	0.6010	51.78	3.79	40.81	3.28	76	0.544
Carbon Velos	0.5587	66.22	4.25	53.89	3.97	84	0.545
MXT-10 Foam	0.5804	64.11	4.05	50.28	3.76	76	0.518
MXT-10 Wood	0.5738	60.91	4.18	50.64	3.93	89	0.518
Axia ILF	0.5688	54.61	3.47	44.91	3.30	63	0.483
Axia Formula	0.5731	56.20	3.65	48.63	3.43	71	0.484
r	-0.74	-0.53	-0.64	-0.53	0.00	-0.66	
$V = r^2$	0.5408	0.2764	0.4120	0.2853	0.0000	0.4354	

	Shooting Efficiency η	Position 1 Decay Time [s]	Position 3 P2P	Position 3 RMS	Position 3 [(m/s^2) / Nm] P2P	Position 3 [(m/s^2) / Nm] RMS	Position 3 Filter at 500 Hz [(m/s^2) / Nm] P2P	Position 3 Filter at 500 Hz [(m/s^2) / Nm] RMS	Damage	Position 3 Decay Time [s]	Max Peak [dB]	SPL [dB]
Motive C5	0.581	0.1719	437.43	27.84	62.64	3.99	45.23	3.71	73	0.1882	93.53	84.24
NS Foam	0.634	0.0858	572.64	32.30	76.15	4.29	53.97	3.80	75	0.1429	97.27	87.59
NS Wood	0.620	0.0991	667.64	34.47	85.58	4.42	55.77	3.74	78	0.0946	102.31	92.51
Sx+	0.577	0.0919	415.29	30.38	51.78	3.79	40.81	3.28	76	0.1691	96.39	87.17
Carbon Velos	0.645	0.0915	518.35	33.28	66.22	4.25	53.89	3.97	84	0.1254	96.84	87.28
MXT-10 Foam	0.626	0.1000	557.41	35.18	64.11	4.05	50.28	3.76	76	0.1492	96.55	87.49
MXT-10 Wood	0.617	0.0896	559.10	38.35	60.91	4.18	50.64	3.93	89	0.1391	96.81	87.62
Axia ILF	0.593	0.1207	503.71	32.01	54.61	3.47	44.91	3.30	63	0.1535	95.14	85.92
Axia Formula	0.589	0.0975	540.32	35.10	56.20	3.65	48.63	3.43	71	0.1271	95.64	86.19
r	-0.53	0.63	0.48	0.63	0.73	0.87	0.80	0.55	-0.57	0.47	0.46	
$V = r^2$	0.2768	0.3931	0.2310	0.3927	0.5401	0.7547	0.6354	0.3033	0.3223	0.2237	0.2113	

	Dimentionless Initial Velocity v	Avg. Stiffness	Avg. Smoothness	Position 1 P2P	Position 1 RMS	Position 1 Filter at 500 Hz [(m/s^2) / Nm] P2P	Position 1 Filter at 500 Hz [(m/s^2) / Nm] RMS	Damage	Position 1 Decay Time [s]	Speed [m/s]	Position 3 Filter at P2P	RMS	Damage	Leq/Poundage [1/N]
Motive C5	2.323	0.8337	0.0019	2102.50	148.20	222.34	20.11	357	0.1719	46.8	315.84	25.92	4981	0.631
NS Foam	2.131	0.8419	0.0011	2659.51	173.11	283.32	20.70	466	0.0858	50.7	405.87	28.59	5551	0.615
NS Wood	2.146	0.8747	0.0013	2578.46	171.16	232.82	19.04	388	0.0991	51.2	435.09	29.20	5966	0.650
Sx+	2.141	0.8350	0.0012	2540.91	173.53	248.84	19.41	373	0.0919	50.4	327.32	26.27	5955	0.544
Carbon Velos	2.154	0.7866	0.0009	2421.94	157.07	254.00	18.49	369	0.0915	50.6	421.83	31.04	6416	0.545
MXT-10 Foam	2.076	0.8416	0.0029	2750.79	171.56	206.61	17.13	337	0.1000	51.7	437.18	32.70	6518	0.518
MXT-10 Wood	2.060	0.8859	0.0027	2721.04	172.14	200.40	16.05	301	0.0896	52.6	464.80	36.04	8022	0.518
Axia ILF	2.049	0.8389	0.0030	2670.63	157.24	188.05	15.50	318	0.1207	51.3	414.22	30.40	5673	0.483
Axia Formula	2.038	0.8819	0.0026	2640.09	154.50	207.57	14.31	270	0.0975	52.7	467.52	32.94	6667	0.484
r	-0.40	-0.50	-0.93	-0.37	0.38	0.76	0.43	0.70	-0.96	-0.78	-0.73	-0.63	0.75	
$V = r^2$	0.1631	0.2546	0.8576	0.1344	0.1434	0.5761	0.1866	0.4883	0.9187	0.6016	0.5370	0.4025	0.5629	

The static quality coefficient q is strongly inversely correlated to the mechanical accelerations in Position 3 (P2P and RMS), scaled and filtered-scaled. The higher the coefficient q, the lower the mechanical vibrations in the riser. The coefficient q is also strongly inversely correlated to the scaled equivalent continuous sound level ($L_{eq}/Poundage$). The higher the coefficient q, the lower the radiated sound of the bow.

The shooting efficiency η is strongly correlated to the mechanical accelerations in the riser (Position 3) for both original, scaled and filtered-scaled data. The efficiency η is inversely correlated to the decay time in both Positions 1 and 3. The higher the efficiency η, the higher the vibrations in the riser and the lower the time-to-rest of the limbs. The first result is quite unexpected but could be the explanation for why the limbs' efficiency is lower in the newer limbs compared to the older ones (Axia limbs compared to Carbon Velos, MXT compared to NS). The efficiency η is moderately directly correlated to the sound metrics: the higher the efficiency η, the higher the sound of the limbs on shooting.

The dimensionless initial velocity v is moderately inversely correlated with the average stiffness and smoothness of the DFCs, so it is related to the shape of the DFCs. The higher the average stiffness and smoothness the lower the velocity v. The velocity v is inversely correlated with the mechanical vibration of the limbs (P2P at Position 1, original data) and of the riser (Position 3, filtered data) and directly correlated to the mechanical vibration of the limbs (RMS at Position 1, filtered-scaled data).

The last result is quite unexpected: more energy in the vibration of the bow means less energy transferred to the arrow. It is suggested that the direct correlation with the mechanical vibration of the limbs (RMS at Position 1, filtered-scaled data) is a numerical occurrence. The velocity v is directly correlated to $L_{eq}/Poundage$. The higher the initial velocity, the higher the sound of the bow on shooting.

Conclusion

Nine sets of limbs from four manufacturers were tested for objective metrics and measurable quantities related to the performance of the limbs on shooting and subjective metrics, the perceived performance of the archers on shooting. The two sets of data were compared using the Pearson correlation coefficient to understand the relationships between objective and subjective metrics and to obtain a better understanding of the archer-bow interaction. Three quality coefficients were used to evaluate the static and dynamic performance of the bow. The static quality coefficient q, the shooting efficiency η and the dimensionless initial velocity v are related to different engineering metrics and could be used to evaluate the relative performance of the limbs. The archers rank the tested limbs based on subjective metrics (average stiffness and perceived vibrations) more than on objective metrics. The vibration of the bow could be divided into mechanical vibrations mainly perceived by the archer coming from the riser (Position 3 on the riser, next to the archer's hand) and radiated sound, mainly perceived coming from limbs and string. In line with previous works, the results show a moderate correlation between the filtered vibrations at Position 3 and the perceived vibration of the bow. Compared to previous works, changing the limbs during each test created a new testing situation with new correlations between the results. The archers are aware of the vibrations on the limbs (Position 1) only as radiated sound and are capable of correctly evaluating the stiffness of the limbs during the draw but cannot perceive the smoothness of the limbs. The archers are also capable of perceiving the speed of the arrows with astonishing precision. Contrary to previous results, the decay time is now strongly related to the acceleration metrics implying that the decay time is a characteristic of the limbs.

This work shows that the proposed methodology is successful in studying the performance of sporting equipment. The study of the correlation between objective and subjective metrics provides a deeper insight into the problem compared to a pure performance-based approach, and this knowledge can be used to design better archery equipment from the perspective of both performance and user experience. The proposed methodology successfully applied to archery equipment, could be applied to any other sporting equipment where the user experience is as important as the technical performance of the design.

Disclaimer

The study was approved by the Human Research Ethics Committee (Non-Medical) of the University of the Witwatersrand to include the use of human participants. The three documents used in this study, the Introduction letter, the Consent form and the Questionnaire, are part of the ethics protocol defined in the Research Ethics document H22/01/25 which was approved by the Human Research Ethics Committee on the 28th of January 2022. All participants in the research were fully aware of being part of the tests for the collection of data for this academic study, and all participants signed the Consent form reported in the Research Ethics document.

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Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

Data

All data used in the paper will be available on request. Please contact the corresponding author by email.

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Appendix A

The following data report the DFC (draw force in N vs. draw length in mm) for the static tests. The first set of data reports the loading and unloading test for the Limbs Winner Motive C5. The second set of data reports the loading tests for the tested nine sets of limbs.

Winner Motive C5				
Draw [in]	Draw [mm]	Effective Draw [mm]	Loading Force [N]	Unloading Force [N]
9.125	231.8	0.0	0.00	0.00
10	254.0	22.2	12.38	12.05
10.5	266.7	34.9	18.64	18.95
11	279.4	47.6	24.82	25.00
11.5	292.1	60.3	30.45	30.57
12	304.8	73.0	35.94	35.78
12.5	317.5	85.7	41.00	40.80
13	330.2	98.4	45.90	45.44
13.5	342.9	111.1	49.90	49.52
14	355.6	123.8	54.10	53.49
14.5	368.3	136.5	57.99	57.22
15	381.0	149.2	61.70	60.86
15.5	393.7	161.9	65.25	64.38
16	406.4	174.6	68.57	67.70
16.5	419.1	187.3	71.80	70.68
17	431.8	200.0	74.98	73.59
17.5	444.5	212.7	77.94	76.62
18	457.2	225.4	80.75	79.57
18.5	469.9	238.1	83.61	82.32
19	482.6	250.8	86.20	85.13
19.5	495.3	263.5	89.22	88.11
20	508.0	276.2	92.06	91.13
20.5	520.7	288.9	94.82	93.56
21	533.4	301.6	97.56	96.24
21.5	546.1	314.3	100.41	99.12
22	558.8	327.0	103.32	102.00
22.5	571.5	339.7	106.12	104.98
23	584.2	352.4	109.14	107.98
23.5	596.9	365.1	112.23	110.95
24	609.6	377.8	115.27	114.05
24.5	622.3	390.5	118.41	117.18
25	635.0	403.2	121.54	120.48
25.5	647.7	415.9	125.00	123.86
26	660.4	428.6	128.28	127.30
26.5	673.1	441.3	131.80	130.70
27	685.8	454.0	135.42	134.35
27.5	698.5	466.7	139.05	138.10
28	711.2	479.4	142.89	141.91
28.5	723.9	492.1	146.60	145.75
29	736.6	504.8	150.53	149.88
29.5	749.3	517.5	154.70	154.26
30	762.0	530.2	158.90	158.90

Draw [in]	Draw [mm]	Effective Draw [mm]	Motive C5 Force [N]	NS Foam Force [N]	NS Wood Force [N]	Carbon Velos Force [N]	MXT-10 Foam Force [N]	MXT-10 Wood Force [N]	Axia ILF Force [N]	Axia Formula Force [N]
9.125	231.8	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	254.0	22.2	12.38	14.05	14.82	12.95	18.94	19.10	20.25	23.64
10.5	266.7	34.9	18.64	21.46	22.62	21.53	28.23	28.88	29.45	33.70
11	279.4	47.6	24.82	28.08	29.47	28.65	36.76	37.84	37.93	42.82
11.5	292.1	60.3	30.45	34.15	35.68	35.78	44.52	45.93	45.85	50.81
12	304.8	73.0	35.94	39.89	42.02	41.98	51.38	53.16	52.72	58.70
12.5	317.5	85.7	41.00	45.06	47.42	47.95	57.98	60.12	59.35	65.44
13	330.2	98.4	45.90	49.90	52.54	53.23	63.92	66.62	65.35	72.06
13.5	342.9	111.1	49.90	54.65	57.32	58.42	69.60	72.34	71.52	77.90
14	355.6	123.8	54.10	59.02	61.65	63.15	75.15	78.18	76.52	83.82
14.5	368.3	136.5	57.99	62.90	65.70	67.59	80.30	83.38	81.85	88.91
15	381.0	149.2	61.70	66.80	69.75	71.69	85.03	88.76	86.52	93.73
15.5	393.7	161.9	65.25	70.65	73.72	75.93	89.70	93.33	91.30	98.37
16	406.4	174.6	68.57	73.95	77.25	79.62	94.24	98.15	95.77	103.08
16.5	419.1	187.3	71.80	77.42	80.75	83.46	98.21	102.52	99.91	107.41
17	431.8	200.0	74.98	80.62	83.95	86.85	102.34	106.45	103.83	111.44
17.5	444.5	212.7	77.94	83.74	87.26	90.12	105.98	110.68	107.72	115.21
18	457.2	225.4	80.75	86.70	90.40	93.30	109.72	114.48	111.51	118.88
18.5	469.9	238.1	83.61	89.65	93.42	96.45	113.01	118.21	115.06	122.47
19	482.6	250.8	86.20	92.60	96.48	99.45	115.95	121.54	118.72	126.10
19.5	495.3	263.5	89.22	95.55	99.63	102.54	118.98	124.88	122.35	129.71
20	508.0	276.2	92.06	98.62	102.85	105.75	122.20	128.21	125.78	133.45
20.5	520.7	288.9	94.82	101.52	105.85	108.80	125.30	131.37	129.42	136.93
21	533.4	301.6	97.56	104.77	109.02	111.84	128.15	134.60	133.07	140.50
21.5	546.1	314.3	100.41	107.95	112.19	114.75	131.26	137.81	136.38	144.00
22	558.8	327.0	103.32	110.72	115.43	117.97	134.80	141.03	140.10	147.62
22.5	571.5	339.7	106.12	113.78	118.68	121.10	137.85	144.40	143.79	151.26
23	584.2	352.4	109.14	116.95	122.05	124.40	140.52	147.82	147.40	155.10
23.5	596.9	365.1	112.23	120.34	125.02	127.66	143.50	151.29	151.13	158.91
24	609.6	377.8	115.27	123.68	128.52	130.84	146.82	154.81	155.02	162.72
24.5	622.3	390.5	118.41	127.42	132.05	134.33	150.32	158.57	159.05	166.95
25	635.0	403.2	121.54	130.92	135.71	137.82	153.83	162.28	163.04	170.63
25.5	647.7	415.9	125.00	134.05	139.29	141.36	157.42	166.35	167.05	174.83
26	660.4	428.6	128.28	137.90	143.14	144.95	161.28	170.40	171.20	179.21
26.5	673.1	441.3	131.80	141.95	147.10	148.51	164.92	174.32	175.45	183.14
27	685.8	454.0	135.42	145.93	151.23	152.42	168.95	178.60	179.70	187.98
27.5	698.5	466.7	139.05	150.00	155.39	156.22	173.55	183.01	184.49	192.30
28	711.2	479.4	142.89	153.88	159.64	160.17	177.92	187.82	188.75	196.73
28.5	723.9	492.1	146.60	158.66	164.32	164.31	181.65	192.58	193.65	201.54
29	736.6	504.8	150.53	162.60	168.84	168.59	186.22	197.34	198.35	206.04
29.5	749.3	517.5	154.70	167.26	173.59	172.96	190.81	201.98	203.51	211.04
30	762.0	530.2	158.90	171.70	178.52	177.90	195.70	207.90	208.52	219.15

Draw [in]	Draw [mm]	Effective Draw [mm]	Sx+ Force [N]
8.875	225.4	0.0	0.00
10	254.0	28.6	21.20
10.5	266.7	41.3	29.56
11	279.4	54.0	36.73
11.5	292.1	66.7	43.68
12	304.8	79.4	50.20
12.5	317.5	92.1	56.12
13	330.2	104.8	62.02
13.5	342.9	117.5	66.95
14	355.6	130.2	72.12
14.5	368.3	142.9	77.15
15	381.0	155.6	81.87
15.5	393.7	168.3	86.36
16	406.4	181.0	90.42
16.5	419.1	193.7	94.58
17	431.8	206.4	98.52
17.5	444.5	219.1	102.20
18	457.2	231.8	106.02
18.5	469.9	244.5	109.45
19	482.6	257.2	112.80
19.5	495.3	269.9	115.97
20	508.0	282.6	118.95
20.5	520.7	295.3	121.94
21	533.4	308.0	124.72
21.5	546.1	320.7	127.65
22	558.8	333.4	130.37
22.5	571.5	346.1	133.10
23	584.2	358.8	135.87
23.5	596.9	371.5	138.38
24	609.6	384.2	140.91
24.5	622.3	396.9	143.73
25	635.0	409.6	146.32
25.5	647.7	422.3	149.15
26	660.4	435.0	151.94
26.5	673.1	447.7	154.85
27	685.8	460.4	157.71
27.5	698.5	473.1	160.75
28	711.2	485.8	164.12
28.5	723.9	498.5	167.40
29	736.6	511.2	170.95
29.5	749.3	523.9	174.48
30	762.0	536.6	178.37

Appendix B

The following data are reported in the global coordinate system. P2P is the root sum of squares of the P2P in the three directions X, Y and Z. RMS is the root sum of squares of the RMS in the three directions X, Y and Z, as well as Damage is the root sum of squares of the Damages in the three directions X, Y and Z. P2P and RMS original data are in units of g (standard Earth acceleration), Decay Time is in seconds while the Damage is dimensionless. The data were then converted into the units of m/s^2 and scaled using the *maximum energy* (Max E) defined as $|\overline{OD}| \cdot \bar{F}(|\overline{OD}|)$ where $|\overline{OD}|$ is equal to 28" draw (711.2 mm) and $\bar{F}(|\overline{OD}|)$ is the measured draw force for each set of limbs.

Position 1 - Original Data

Limbs' Name	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS	Decay
	[g]								Time [s]
Motive C5	1786.94	876.18	677.97	2102.50	131.55	61.18	30.24	148.20	0.1719
NS Foam	2196.47	1011.63	1106.84	2659.51	156.21	65.90	34.98	173.11	0.0858
NS Wood	2129.65	1243.52	752.81	2578.46	147.45	77.73	38.89	171.16	0.0991
SX+	2145.03	1130.99	758.91	2540.91	155.19	70.82	31.86	173.53	0.0919
Carbon Velos	1947.26	1008.84	1027.72	2421.94	141.31	57.00	38.15	157.07	0.0915
MXT-10 Foam	2128.24	1514.91	861.68	2750.79	151.01	74.11	33.69	171.56	0.1000
MXT-10 Wood	2137.34	1363.23	988.66	2721.04	149.13	76.80	38.68	172.14	0.0896
Axia ILF	2192.18	1251.89	871.41	2670.63	139.01	66.01	32.31	157.24	0.1207
Axia Formula	2249.15	1048.15	901.56	2640.09	137.64	62.13	32.64	154.50	0.0975

Limbs' Name	Max E [Nm]	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS
	@ 28in Draw				[(m/s^2) / Nm]				
Motive C5	68.50	255.91	125.48	97.09	301.10	18.84	8.76	4.33	21.22
NS Foam	73.77	292.09	134.53	147.19	353.66	20.77	8.76	4.65	23.02
NS Wood	76.53	272.98	159.40	96.50	330.51	18.90	9.96	4.99	21.94
Sx+	78.68	267.45	141.02	94.62	316.81	19.35	8.83	3.97	21.64
Carbon Velos	76.79	248.78	128.89	131.30	309.42	18.05	7.28	4.87	20.07
MXT-10 Foam	85.29	244.77	174.23	99.10	316.38	17.37	8.52	3.87	19.73
MXT-10 Wood	90.04	232.86	148.52	107.72	296.46	16.25	8.37	4.21	18.75
Axia ILF	90.49	237.66	135.72	94.47	289.53	15.07	7.16	3.50	17.05
Axia Formula	94.31	233.95	109.02	93.78	274.61	14.32	6.46	3.40	16.07

Position 3 - Original Data

Limbs' Name	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS	Decay
	[g]								Time [s]
Motive C5	386.50	109.90	172.89	437.43	24.71	4.36	12.05	27.84	0.1882
NS Foam	506.65	146.79	222.90	572.64	29.12	6.35	12.44	32.30	0.1429
NS Wood	537.99	210.31	334.79	667.64	29.22	8.10	16.39	34.47	0.0946
SX+	324.84	115.22	231.67	415.29	24.93	5.51	16.47	30.38	0.1691
Carbon Velos	424.58	105.58	277.97	518.35	27.64	6.03	17.52	33.28	0.1254
MXT-10 Foam	451.86	120.82	303.19	557.41	31.97	5.50	13.61	35.18	0.1492
MXT-10 Wood	494.15	120.02	232.40	559.10	34.73	5.69	15.23	38.35	0.1391
Axia ILF	449.68	84.62	210.59	503.71	28.71	4.63	13.38	32.01	0.1535
Axia Formula	472.74	99.17	242.12	540.32	31.48	5.90	14.36	35.10	0.1271

Limbs' Name	Max E [Nm]	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS
	@ 28in Draw				[(m/s^2) / Nm]				
Motive C5	68.50	55.35	15.74	24.76	62.64	3.54	0.62	1.73	3.99
NS Foam	73.77	67.37	19.52	29.64	76.15	3.87	0.84	1.65	4.29
NS Wood	76.53	68.96	26.96	42.91	85.58	3.75	1.04	2.10	4.42
Sx+	78.68	40.50	14.37	28.89	51.78	3.11	0.69	2.05	3.79
Carbon Velos	76.79	54.24	13.49	35.51	66.22	3.53	0.77	2.24	4.25
MXT-10 Foam	85.29	51.97	13.90	34.87	64.11	3.68	0.63	1.57	4.05
MXT-10 Wood	90.04	53.84	13.08	25.32	60.91	3.78	0.62	1.66	4.18
Axia ILF	90.49	48.75	9.17	22.83	54.61	3.11	0.50	1.45	3.47
Axia Formula	94.31	49.17	10.32	25.18	56.20	3.27	0.61	1.49	3.65

The original mechanical vibration data were filtered with a lowpass filter at 500 Hz and scaled as for the original data.

Position 1 - Filtered Data at 500 Hz

Limbs' Name	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS	Damage X	Damage Y	Damage Z	Damage
				[g]								
Motive C5	1402.78	605.89	274.91	1552.57	127.85	53.97	21.63	140.45	22597.6	7499.1	5621.7	24464.1
NS Foam	1992.69	712.34	246.89	2130.54	144.66	53.12	21.76	155.63	32733.6	9191.4	5075.0	34376.2
NS Wood	1587.85	797.59	376.34	1816.33	132.66	60.57	28.09	148.52	27118.9	9931.0	6772.5	29663.5
SX+	1853.40	699.35	242.56	1995.75	144.90	54.01	18.17	155.70	27864.4	8276.6	4287.5	29382.1
Carbon Velos	1834.47	688.94	335.55	1988.09	134.17	47.61	25.86	144.69	26722.3	6802.8	6527.5	28336.7
MXT-10 Foam	1570.85	814.78	309.30	1796.41	135.98	57.46	19.95	148.97	27693.1	5712.3	4930.0	28702.7
MXT-10 Wood	1601.59	823.38	374.27	1839.33	133.16	57.44	25.77	147.30	25586.2	5840.7	6755.0	27099.8
Axia ILF	1542.01	749.12	264.29	1734.59	129.63	56.63	20.86	142.99	27258.3	8214.5	4246.7	28784.2
Axia Formula	1787.44	808.75	364.88	1995.53	125.81	51.29	21.60	137.57	24358.6	5842.0	4642.5	25475.9

Limbs' Name	Max E [Nm]	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS	Damage X	Damage Y	Damage Z	Damage
	@ 28in Draw				[(m/s^2) / Nm]						[1 / Nm]		
Motive C5	68.50	200.89	86.77	39.37	222.34	18.31	7.73	3.10	20.11	329.9	109.5	82.1	357.1
NS Foam	73.77	264.99	94.73	32.83	283.32	19.24	7.06	2.89	20.70	443.7	124.6	68.8	466.0
NS Wood	76.53	203.53	102.24	48.24	232.82	17.00	7.76	3.60	19.04	354.3	129.8	88.5	387.6
Sx+	78.68	231.09	87.20	30.24	248.84	18.07	6.73	2.26	19.41	354.2	105.2	54.5	373.4
Carbon Velos	76.79	234.37	88.02	42.87	254.00	17.14	6.08	3.30	18.49	348.0	88.6	85.0	369.0
MXT-10 Foam	85.29	180.67	93.71	35.57	206.61	15.64	6.61	2.29	17.13	324.7	67.0	57.8	336.5
MXT-10 Wood	90.04	174.49	89.71	40.78	200.40	14.51	6.26	2.81	16.05	284.2	64.9	75.0	301.0
Axia ILF	90.49	167.17	81.21	28.65	188.05	14.05	6.14	2.26	15.50	301.2	90.8	46.9	318.1
Axia Formula	94.31	185.92	84.12	37.95	207.57	13.09	5.34	2.25	14.31	258.3	61.9	49.2	270.1

Position 3 - Filtered Data at 500 Hz

Limbs' Name	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS	Damage X	Damage Y	Damage Z	Damage
				[g]								
Motive C5	294.20	26.24	111.86	315.84	23.47	2.09	10.80	25.92	4102.5	520.0	2776.7	4981.0
NS Foam	392.60	43.24	93.39	405.87	26.87	3.29	9.21	28.59	4935.0	696.0	2444.2	5550.9
NS Wood	400.69	35.75	165.77	435.09	26.18	2.94	12.59	29.20	4842.5	755.3	3402.5	5966.3
SX+	283.61	40.19	158.39	327.32	22.05	3.06	13.95	26.27	4067.5	733.8	4287.5	5955.3
Carbon Velos	368.88	58.50	196.07	421.83	26.25	4.53	15.93	31.04	4815.0	994.2	4121.7	6415.7
MXT-10 Foam	409.15	44.35	147.52	437.18	30.69	2.76	10.93	32.70	5830.0	610.0	2850.0	6517.9
MXT-10 Wood	438.38	43.15	148.32	464.80	33.45	3.04	13.08	36.04	6562.5	776.5	4548.3	8022.3
Axia ILF	374.58	37.58	172.79	414.22	27.84	2.97	11.86	30.40	4830.0	657.3	2901.7	5672.8
Axia Formula	425.65	65.40	181.99	467.52	30.32	4.54	12.03	32.94	5904.2	939.2	2950.8	6667.0

Limbs' Name	Max E [Nm]	P2P - X	P2P - Y	P2P - Z	P2P	RMS - X	RMS - Y	RMS - Z	RMS	Damage X	Damage Y	Damage Z	Damage
	@ 28in Draw				[(m/s^2) / Nm]						[1 / Nm]		
Motive C5	68.50	42.13	3.76	16.02	45.23	3.36	0.30	1.55	3.71	59.9	7.6	40.5	72.7
NS Foam	73.77	52.21	5.75	12.42	53.97	3.57	0.44	1.22	3.80	66.9	9.4	33.1	75.2
NS Wood	76.53	51.36	4.58	21.25	55.77	3.36	0.38	1.61	3.74	63.3	9.9	44.5	78.0
Sx+	78.68	35.36	5.01	19.75	40.81	2.75	0.38	1.74	3.28	51.7	9.3	54.5	75.7
Carbon Velos	76.79	47.13	7.47	25.05	53.89	3.35	0.58	2.04	3.97	62.7	12.9	53.7	83.6
MXT-10 Foam	85.29	47.06	5.10	16.97	50.28	3.53	0.32	1.26	3.76	68.4	7.2	33.4	76.4
MXT-10 Wood	90.04	47.76	4.70	16.16	50.64	3.64	0.33	1.42	3.93	72.9	8.6	50.5	89.1
Axia ILF	90.49	40.61	4.07	18.73	44.91	3.02	0.32	1.29	3.30	53.4	7.3	32.1	62.7
Axia Formula	94.31	44.27	6.80	18.93	48.63	3.15	0.47	1.25	3.43	62.6	10.0	31.3	70.7

Appendix C

The data from the Questionnaires are reported in the following tables.
The *stiffness* of the string on draw is evaluated for the beginning, the middle and the end of the draw. The modes of the data are averaged using a weighted average, with weights equal to 0.25 for the beginning and middle stiffness data, and a weight equal to 0.50 for the stiffness data at the end of the draw. The weighted average is necessary to approximate the archers' evaluation of the limbs. The behaviour at the end of the draw is the most important one and is the one that most affects the score.

Stiffness Very Stiff [1] Stiff [2] Normal [3] Soft [4] Very Soft [5]

At the Beginning:	Archer 1	Archer 2	Archer 3	Archer 4	Archer 5	Archer 6	Archer 7	Archer 8	Archer 9	Archer 10	Mode	Median
Motive C5	2	2	2	3	3	3	4	2	2	2	2.0	2.0
NS Foam	4	4	4	4	4	4	4	3	4	4	4.0	4.0
NS Wood	3	4	3	2	2	2	2	3	3	3	3.0	3.0
Sx+	3	5	3	2	4	2	3	2	3	4	3.0	3.0
Carbon Velos	4	4	4	3	3	3	2	3	4	3	3.0	3.0
MXT-10 Foam	3	4	3	4	3	4	1	3	4	4	4.0	3.5
MXT-10 Wood	2	2	2	2	2	1	3	2	2	2	2.0	2.0
Axia ILF	3	2	3	3	1	3	3	2	3	3	3.0	3.0
Axia Formula	4	2	4	3	2	2	3	2	3	3	2.0	3.0

Middle Draw:	Archer 1	Archer 2	Archer 3	Archer 4	Archer 5	Archer 6	Archer 7	Archer 8	Archer 9	Archer 10	Mode	Median
Motive C5	2	2	2	3	3	2	4	3	2	2	2.0	2.0
NS Foam	4	4	4	4	4	4	3	4	4	4	4.0	4.0
NS Wood	3	4	3	2	2	2	2	3	3	3	3.0	3.0
Sx+	3	5	3	3	4	2	3	2	3	4	3.0	3.0
Carbon Velos	4	4	3	3	3	3	2	3	3	3	3.0	3.0
MXT-10 Foam	3	4	3	4	3	3	1	3	4	4	3.0	3.0
MXT-10 Wood	2	2	2	2	2	1	3	2	2	2	2.0	2.0
Axia ILF	3	2	3	3	1	3	2	2	3	3	3.0	3.0
Axia Formula	3	2	3	3	2	2	2	2	3	3	3.0	2.5

At the End:	Archer 1	Archer 2	Archer 3	Archer 4	Archer 5	Archer 6	Archer 7	Archer 8	Archer 9	Archer 10	Mode	Median
Motive C5	2	2	2	3	3	3	3	3	2	2	2.0	2.5
NS Foam	4	4	4	4	2	2	2	4	4	4	4.0	4.0
NS Wood	3	2	3	1	1	1	1	1	3	3	1.0	1.5
Sx+	4	5	3	1	3	1	2	2	4	5	4.0	3.0
Carbon Velos	2	4	1	3	3	3	1	3	2	1	3.0	2.5
MXT-10 Foam	3	4	3	4	3	3	1	3	4	4	3.0	3.0
MXT-10 Wood	2	3	2	2	2	1	3	2	2	2	2.0	2.0
Axia ILF	2	2	3	3	1	3	2	2	3	3	3.0	2.5
Axia Formula	2	2	2	3	1	1	2	2	1	2	2.0	2.0

	Stiffness - Mode			Avg.
	Beginning	Middle	End	Stiffness
Motive C5	2	2	2	2.00
NS Foam	4	4	4	4.00
NS Wood	3	3	1	2.00
Sx+	3	3	4	3.50
Carbon Velos	3	3	3	3.00
MXT-10 Foam	4	3	3	3.25
MXT-10 Wood	2	2	2	2.00
Axia ILF	3	3	3	3.00
Axia Formula	2	3	2	2.25

The smoothness is evaluated by asking the archers if the draw action is equally smooth at the beginning, middle and end of the drawing action. If the archer felt a change in smoothness, then he/she was asked to evaluate the change. A reply No/+ = -, for example, means that the drawing was not continuously smooth, but it was soft at the beginning ("+"), normal in the middle ("=") and stiff at the end ("-") of the drawing action. The data are converted into numbers assigning -1 to a stiff evaluation, 0 to a normal evaluation, and +1 to a soft evaluation. The summary of the results is reported in the "Summary" table, where the results are divided by the number of archers. The average smoothness is calculated using a weighted average, with weights equal to 0.25 for the beginning and middle smoothness data, and a weight equal to 0.50 for the smoothness data at the end of the draw.

Smoothness

	Archer 1	Archer 2	Archer 3	Archer 4	Archer 5	Archer 6	Archer 7	Archer 8	Archer 9	Archer 10	Result "Yes"	Result "No"
Motive C5	Yes	Yes	No/==-	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9	1
NS Foam	Yes	Yes	Yes	Yes	No/==-	Yes	Yes	Yes	Yes	Yes	9	1
NS Wood	Yes	No/==-	Yes	No/==-	No/==-	Yes	No/+=-	Yes	Yes	Yes	6	4
Sx+	No/==+	Yes	Yes	Yes	No/==-	Yes	Yes	No/==-	No/==+	No/==+	5	5
Carbon Velos	No/+=-	Yes	No/==-	No/-==	Yes	No/==+	No/==-	Yes	No/+=-	No/==-	3	7
MXT-10 Foam	No/==+	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	9	1
MXT-10 Wood	Yes	Yes	No/==-	Yes	Yes	No/=-=	Yes	Yes	Yes	Yes	8	2
Axia ILF	Yes	Yes	Yes	Yes	Yes	Yes	No/-==	Yes	Yes	Yes	9	1
Axia Formula	No/==-	Yes	No/==-	No/+==	Yes	Yes	No/-==	Yes	No/==-	No/==-	4	6

	Beginning			Middle			End			Summary			Avg.
	Stiff	Normal	Soft	Stiff	Normal	Soft	Stiff	Normal	Soft	Beginning	Middle	End	Smoothness
Motive C5		10			10		1	9		0	0	-0.1	-0.05
NS Foam		10			10		1	9		0	0	-0.1	-0.05
NS Wood		9	1		10		4	6		0.1	0	-0.4	-0.18
Sx+		10			10		2	5	3	0	0	0.1	0.05
Carbon Velos	1	7	2		10		5	4	1	0.1	0	-0.4	-0.18
MXT-10 Foam		10			10			9	1	0	0	0.1	0.05
MXT-10 Wood		10		1	9		1	9		0	-0.1	-0.1	-0.08
Axia ILF	1	9			10			10		-0.1	0	0	-0.03
Axia Formula	1	8	1		10		4	6		0	0	-0.4	-0.20

Speed of the Limbs Very Quick [1] Quick [2] Normal [3] Slow [4] Very Slow [5]

	Archer 1	Archer 2	Archer 3	Archer 4	Archer 5	Archer 6	Archer 7	Archer 8	Archer 9	Archer 10	Mode	Median
Motive C5	4	4	4	3	4	4	4	3	4	4	4.0	4.0
NS Foam	3	2	3	3	2	1	2	2	3	4	3.0	2.5
NS Wood	3	2	2	2	2	1	2	3	3	3	2.0	2.0
Sx+	4	2	2	1	2	1	3	3	3	3	3.0	2.5
Carbon Velos	3	3	2	2	3	2	2	3	2	2	2.0	2.0
MXT-10 Foam	4	2	3	1	2	3	1	1	3	2	2.0	2.0
MXT-10 Wood	3	2	2	1	2	3	1	1	1	1	1.0	1.5
Axia ILF	2	3	3	1	1	2	2	3	2	2	2.0	2.0
Axia Formula	2	2	2	1	1	3	2	2	1	2	2.0	2.0

Vibrations Very High [1] High [2] Normal [3] Low [4] Very Low [5]

	Archer 1	Archer 2	Archer 3	Archer 4	Archer 5	Archer 6	Archer 7	Archer 8	Archer 9	Archer 10	Mode	Median
Motive C5	1	3	1	3	2	4	4	3	2	2	3.0	2.5
NS Foam	3	3	4	3	1	3	2	2	3	4	3.0	3.0
NS Wood	3	2	3	1	1	1	2	3	3	3	3.0	2.5
Sx+	4	4	4	2	3	1	3	1	4	4	4.0	3.5
Carbon Velos	3	4	4	3	4	3	2	4	3	3	3.0	3.0
MXT-10 Foam	4	3	4	3	4	4	3	3	4	4	4.0	4.0
MXT-10 Wood	3	4	2	2	2	3	2	3	2	2	2.0	2.0
Axia ILF	3	3	3	3	4	2	3	4	3	3	3.0	3.0
Axia Formula	3	3	4	3	3	4	3	4	3	3	3.0	3.0

Sound Very Noisy [1] Noisy [2] Normal [3] Quiet [4] Very Quiet [5]

	Archer 1	Archer 2	Archer 3	Archer 4	Archer 5	Archer 6	Archer 7	Archer 8	Archer 9	Archer 10	Mode	Median
Motive C5	3	4	2	3	3	2	3	4	2	2	3.0	3.0
NS Foam	4	4	3	4	2	2	2	2	4	3	4.0	3.0
NS Wood	1	3	3	2	1	1	1	2	2	2	1.0	2.0
Sx+	4	4	4	3	3	2	3	2	4	3	4.0	3.0
Carbon Velos	4	4	4	3	3	4	3	4	3	4	4.0	4.0
MXT-10 Foam	4	4	4	4	3	2	2	4	3	4	4.0	4.0
MXT-10 Wood	2	2	3	3	2	4	3	4	2	2	2.0	2.5
Axia ILF	3	2	3	3	4	2	2	3	4	3	3.0	3.0
Axia Formula	3	2	4	3	3	4	2	4	3	4	3.0	3.0

The archers were requested to order the tested limbs according to their preference. To consider the effect of the different poundages, the limbs were divided into three groups depending on the nominal poundage. The preferences relative to the groups are reported in the second table. The absolute preference was calculated by multiplying the preferences relative to the groups by the positions and dividing by the number of archers. For example, for the limbs Motive C5 six archers scored a second position, and four archers scored a third position. The absolute preference is calculated according to the following formula:

Absolute Preference $= \frac{(0\cdot1)+(6\cdot2)+(4\cdot3)}{10} = 2.4$

The ordered absolute preference is reported in the last table.

Preference

		Archer 1	Archer 2	Archer 3	Archer 4	Archer 5	Archer 6	Archer 7	Archer 8	Archer 9	Archer 10	**Mode**	**Median**
Group 1	Motive C5	3	2	3	2	2	2	2	2	3	3	2.0	2.0
	NS Foam	1	1	1	1	1	1	1	1	1	1	1.0	1.0
	NS Wood	2	3	2	3	3	3	3	3	2	2	3.0	3.0
Group 2	Sx+	1	1	1	2	1	2	1	2	1	1	1.0	1.0
	Carbon Velos	2	2	2	1	2	1	2	1	2	2	2.0	2.0
Group 3	MXT-10 Foam	1	1	1	1	1	1	1	2	1	1	1.0	1.0
	MXT-10 Wood	3	4	4	4	4	4	4	4	4	4	4.0	4.0
	Axia ILF	4	2	3	3	3	3	2	3	3	2	3.0	3.0
	Axia Formula	2	3	2	2	2	2	3	1	2	3	2.0	2.0

		1st	2nd	3rd	4th	**Absolute Preference**
Group 1	Motive C5		6	4		2.4
	NS Foam	10				1.0
	NS Wood		4	6		2.6
Group 2	Sx+	7	3			1.3
	Carbon Velos	3	7			1.7
Group 3	MXT-10 Foam	9	1			1.1
	MXT-10 Wood			1	9	3.9
	Axia ILF		3	6	1	2.8
	Axia Formula	1	6	3		2.2

	Absolute Preference
NS Foam	1.0
MXT-10 Foam	1.1
Sx+	1.3
Carbon Velos	1.7
Axia Formula	2.2
Motive C5	2.4
NS Wood	2.6
Axia ILF	2.8
MXT-10 Wood	3.9

Appendix D

The next tables report the Pearson correlation coefficient r and the coefficient of determination $V = r^2$ between experimental metrics and perceived metrics.
The experimental average stiffness is calculated using a weighted average, with weights equal to 0.25 for the beginning and middle stiffness data, and a weight equal to 0.50 for the stiffness data at the end of the draw. To account for the different poundages, the results are then divided by the poundage of the corresponding limb. The experimental stiffness is correlated with the perceived stiffness: stiffness @15in with beginning stiffness, stiffness @21in with middle stiffness, stiffness @28in with end stiffness, and average experimental stiffness with perceived average stiffness.

	Stiffness [N]			Poundage	Avg.	Stiffness - Mode			Avg.
	@15in	@21in	@28in	[N]	Stiffness	Beginning	Middle	End	Stiffness
Motive C5	61.70	97.56	142.89	133.45	0.8337	2.0	2.0	2.0	2.00
NS Foam	66.80	104.77	153.88	142.34	0.8419	4.0	4.0	4.0	4.00
NS Wood	69.75	109.02	159.64	142.34	0.8747	3.0	3.0	1.0	2.00
Sx+	81.87	124.72	164.12	160.14	0.8350	3.0	3.0	4.0	3.50
Carbon Velos	71.69	111.84	160.17	160.14	0.7866	3.0	3.0	3.0	3.00
MXT-10 Foam	85.03	128.15	177.92	169.03	0.8416	4.0	3.0	3.0	3.25
MXT-10 Wood	88.76	134.60	187.82	169.03	0.8859	2.0	2.0	2.0	2.00
Axia ILF	86.52	133.07	188.75	177.93	0.8389	3.0	3.0	3.0	3.00
Axia Formula	93.73	140.50	196.73	177.93	0.8819	2.0	3.0	2.0	2.25
					r	-0.20	-0.10	-0.12	-0.51
					$V = r^2$	0.0398	0.0091	0.0153	0.2556

The experimental average smoothness is calculated using a weighted average, with weights equal to 0.25 for the beginning and middle smoothness data, and a weight equal to 0.50 for the smoothness data at the end of the draw. To account for the different poundages, the results are then divided by the poundage of the corresponding limb. The experimental smoothness is correlated with the perceived smoothness: smoothness @15in with beginning smoothness, smoothness @21in with middle smoothness, smoothness @28in with end smoothness, and average experimental smoothness with perceived average smoothness.

	Smoothness [N/mm]			Poundage	Avg.	Smoothness - Summary			Avg.
	@15in	@21in	@28in	[N]	Smoothness	Beginning	Middle	End	Smoothness
Motive C5	0.2991	0.2004	0.2614	133.45	0.0019	0.0	0.0	-0.1	-0.05
NS Foam	0.2803	0.1206	0.1105	142.34	0.0011	0.0	0.0	-0.1	-0.05
NS Wood	0.3085	0.1488	0.1387	142.34	0.0013	0.1	0.0	-0.4	-0.18
Sx+	0.3575	0.1732	0.1343	160.14	0.0012	0.0	0.0	0.1	0.05
Carbon Velos	0.3095	0.1193	0.0736	160.14	0.0009	0.1	0.0	-0.4	-0.18
MXT-10 Foam	0.4128	0.3374	0.6016	169.03	0.0029	0.0	0.0	0.1	0.05
MXT-10 Wood	0.4143	0.3083	0.5370	169.03	0.0027	0.0	-0.1	-0.1	-0.08
Axia ILF	0.4214	0.3764	0.6761	177.93	0.0030	-0.1	0.0	0.0	-0.03
Axia Formula	0.4265	0.3205	0.5492	177.93	0.0026	0.0	0.0	-0.4	-0.20
					r	-0.56	-0.28	0.31	0.24
					$V = r^2$	0.3123	0.0760	0.0933	0.0569

The next tables report the correlation coefficient between the perceived speed (*speed mode*) and the measured speed (*speed [m/s]*) and between the perceived sound of the limbs (sound *mode*) and the measured sound metrics.

	Speed [m/s]	Speed Mode
Motive C5	46.8	4.0
NS Foam	50.7	3.0
NS Wood	51.2	2.0
Sx+	50.4	3.0
Carbon Velos	50.6	2.0
MXT-10 Foam	51.7	2.0
MXT-10 Wood	52.6	1.0
Axia ILF	51.3	2.0
Axia Formula	52.7	2.0
r	-0.87	
$V = r^2$	0.7634	

	Sound Mode	Max Peak [dB]	SPL [dB]	Leq/Poundage [1/N]
Motive C5	3.0	93.53	84.24	0.631
NS Foam	4.0	97.27	87.59	0.615
NS Wood	1.0	102.31	92.51	0.650
Sx+	4.0	96.39	87.17	0.544
Carbon Velos	4.0	96.84	87.28	0.545
MXT-10 Foam	4.0	96.55	87.49	0.518
MXT-10 Wood	2.0	96.81	87.62	0.518
Axia ILF	3.0	95.14	85.92	0.483
Axia Formula	3.0	95.64	86.19	0.484
r	-0.55	-0.55	-0.28	
$V = r^2$	0.3046	0.3072	0.0802	

The next tables report the correlation coefficients between selected perceived and measured metrics.

	Vibrations	Position 1		Position 1 [(m/s^2) / Nm]		Position 1 Filter at 500 Hz			Position 1 Filter at 500 Hz [(m/s^2) / Nm]			Position 1 Decay
	Mode	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]
Motive C5	3.0	2102.50	148.20	301.10	21.22	1552.57	140.45	24464	222.34	20.11	357	0.1719
NS Foam	3.0	2659.51	173.11	353.66	23.02	2130.54	155.63	34376	283.32	20.70	466	0.0858
NS Wood	3.0	2578.46	171.16	330.51	21.94	1816.33	148.52	29664	232.82	19.04	388	0.0991
Sx+	4.0	2540.91	173.53	316.81	21.64	1995.75	155.70	29382	248.84	19.41	373	0.0919
Carbon Velos	3.0	2421.94	157.07	309.42	20.07	1988.09	144.69	28337	254.00	18.49	369	0.0915
MXT-10 Foam	4.0	2750.79	171.56	316.38	19.73	1796.41	148.97	28703	206.61	17.13	337	0.1000
MXT-10 Wood	2.0	2721.04	172.14	296.46	18.75	1839.33	147.30	27100	200.40	16.05	301	0.0896
Axia ILF	3.0	2670.63	157.24	289.53	17.05	1734.59	142.99	28784	188.05	15.50	318	0.1207
Axia Formula	3.0	2640.09	154.50	274.61	16.07	1995.53	137.57	25476	207.57	14.31	270	0.0975
r		0.01	0.18	0.24	0.24	0.10	0.35	0.18	0.19	0.25	0.20	-0.02
$V = r^2$		0.0000	0.0333	0.0576	0.0576	0.0093	0.1234	0.0339	0.0363	0.0613	0.0419	0.0006

	Sound	Position 1		Position 1 [(m/s^2) / Nm]		Position 1 Filter at 500 Hz			Position 1 Filter at 500 Hz [(m/s^2) / Nm]			Position 1 Decay
	Mode	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]
Motive C5	3.0	2102.50	148.20	301.10	21.22	1552.57	140.45	24464	222.34	20.11	357	0.1719
NS Foam	4.0	2659.51	173.11	353.66	23.02	2130.54	155.63	34376	283.32	20.70	466	0.0858
NS Wood	1.0	2578.46	171.16	330.51	21.94	1816.33	148.52	29664	232.82	19.04	388	0.0991
Sx+	4.0	2540.91	173.53	316.81	21.64	1995.75	155.70	29382	248.84	19.41	373	0.0919
Carbon Velos	4.0	2421.94	157.07	309.42	20.07	1988.09	144.69	28337	254.00	18.49	369	0.0915
MXT-10 Foam	4.0	2750.79	171.56	316.38	19.73	1796.41	148.97	28703	206.61	17.13	337	0.1000
MXT-10 Wood	2.0	2721.04	172.14	296.46	18.75	1839.33	147.30	27100	200.40	16.05	301	0.0896
Axia ILF	3.0	2670.63	157.24	289.53	17.05	1734.59	142.99	28784	188.05	15.50	318	0.1207
Axia Formula	3.0	2640.09	154.50	274.61	16.07	1995.53	137.57	25476	207.57	14.31	270	0.0975
r		-0.04	-0.04	0.15	0.10	0.39	0.26	0.25	0.39	0.20	0.24	-0.11
$V = r^2$		0.0017	0.0017	0.0217	0.0093	0.1495	0.0692	0.0609	0.1498	0.0402	0.0584	0.0111

	Position 1 Decay Time [s]	Position 1		Position 1 [(m/s^2) / Nm]		Position 1 Filter at 500 Hz			Position 1 Filter at 500 Hz [(m/s^2) / Nm]			Speed [m/s]	Speed Mode
		P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage		
Motive C5	0.1719	2102.50	148.20	301.10	21.22	1552.57	140.45	24464	222.34	20.11	357	46.8	4.0
NS Foam	0.0858	2659.51	173.11	353.66	23.02	2130.54	155.63	34376	283.32	20.70	466	50.7	3.0
NS Wood	0.0991	2578.46	171.16	330.51	21.94	1816.33	148.52	29664	232.82	19.04	388	51.2	2.0
Sx+	0.0919	2540.91	173.53	316.81	21.64	1995.75	155.70	29382	248.84	19.41	373	50.4	3.0
Carbon Velos	0.0915	2421.94	157.07	309.42	20.07	1988.09	144.69	28337	254.00	18.49	369	50.6	2.0
MXT-10 Foam	0.1000	2750.79	171.56	316.38	19.73	1796.41	148.97	28703	206.61	17.13	337	51.7	2.0
MXT-10 Wood	0.0896	2721.04	172.14	296.46	18.75	1839.33	147.30	27100	200.40	16.05	301	52.6	1.0
Axia ILF	0.1207	2670.63	157.24	289.53	17.05	1734.59	142.99	28784	188.05	15.50	318	51.3	2.0
Axia Formula	0.0975	2640.09	154.50	274.61	16.07	1995.53	137.57	25476	207.57	14.31	270	52.7	2.0
r		-0.76	-0.71	-0.30	-0.01	-0.84	-0.52	-0.58	-0.31	0.17	-0.13	-0.80	0.62
$V = r^2$		0.5815	0.4995	0.0910	0.0001	0.7033	0.2745	0.3314	0.0954	0.0294	0.0176	0.6375	0.3865

	Vibrations Mode	Position 3		Position 3 [(m/s^2) / Nm]		Position 3 Filter at 500 Hz			Position 3 Filter at 500 Hz [(m/s^2) / Nm]			Position 3 Decay Time [s]
		P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	
Motive C5	3.0	437.43	27.84	62.64	3.99	315.84	25.92	4981	45.23	3.71	73	0.1882
NS Foam	3.0	572.64	32.30	76.15	4.29	405.87	28.59	5551	53.97	3.80	75	0.1429
NS Wood	3.0	667.64	34.47	85.58	4.42	435.09	29.20	5966	55.77	3.74	78	0.0946
Sx+	4.0	415.29	30.38	51.78	3.79	327.32	26.27	5955	40.81	3.28	76	0.1691
Carbon Velos	3.0	518.35	33.28	66.22	4.25	421.83	31.04	6416	53.89	3.97	84	0.1254
MXT-10 Foam	4.0	557.41	35.18	64.11	4.05	437.18	32.70	6518	50.28	3.76	76	0.1492
MXT-10 Wood	2.0	559.10	38.35	60.91	4.18	464.80	36.04	8022	50.64	3.93	89	0.1391
Axia ILF	3.0	503.71	32.01	54.61	3.47	414.22	30.40	5673	44.91	3.30	63	0.1535
Axia Formula	3.0	540.32	35.10	56.20	3.65	467.52	32.94	6667	48.63	3.43	71	0.1271
r		-0.32	-0.41	-0.18	-0.23	-0.42	-0.47	-0.42	-0.37	-0.44	-0.36	0.28
$V = r^2$		0.1046	0.1673	0.0321	0.0538	0.1786	0.2220	0.1758	0.1398	0.1920	0.1301	0.0772

	Position 3 Decay Time [s]	Position 3		Position 3 [(m/s^2) / Nm]		Position 3 Filter at 500 Hz			Position 3 Filter at 500 Hz [(m/s^2) / Nm]			Speed [m/s]	Speed Mode
		P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage		
Motive C5	0.1882	437.43	27.84	62.64	3.99	315.84	25.92	4981	45.23	3.71	73	46.8	4.0
NS Foam	0.1429	572.64	32.30	76.15	4.29	405.87	28.59	5551	53.97	3.80	75	50.7	3.0
NS Wood	0.0946	667.64	34.47	85.58	4.42	435.09	29.20	5966	55.77	3.74	78	51.2	2.0
Sx+	0.1691	415.29	30.38	51.78	3.79	327.32	26.27	5955	40.81	3.28	76	50.4	3.0
Carbon Velos	0.1254	518.35	33.28	66.22	4.25	421.83	31.04	6416	53.89	3.97	84	50.6	2.0
MXT-10 Foam	0.1492	557.41	35.18	64.11	4.05	437.18	32.70	6518	50.28	3.76	76	51.7	2.0
MXT-10 Wood	0.1391	559.10	38.35	60.91	4.18	464.80	36.04	8022	50.64	3.93	89	52.6	1.0
Axia ILF	0.1535	503.71	32.01	54.61	3.47	414.22	30.40	5673	44.91	3.30	63	51.3	2.0
Axia Formula	0.1271	540.32	35.10	56.20	3.65	467.52	32.94	6667	48.63	3.43	71	52.7	2.0
r		-0.87	-0.65	-0.62	-0.46	-0.75	-0.44	-0.39	-0.78	-0.31	-0.30	-0.62	0.64
$V = r^2$		0.7541	0.4272	0.3791	0.2099	0.5617	0.1952	0.1498	0.6141	0.0992	0.0917	0.3884	0.4119

The next tables report the correlation coefficients between the quality coefficients and selected perceived and measured metrics.

				Position 1		Position 1 [(m/s^2) / Nm]		Position 1 Filter at 500 Hz			Position 1 [(m/s^2) / Nm]			Position 1 Decay	Speed	Position 3		Position 3 [(m/s^2) / Nm]		Position 3 Filter at 500 Hz				Position 3 [(m/s^2) / Nm]			Position 3 Decay	Max Peak	SPL	Leq/Poundage
	Absolute Preference	Avg. Stiffness	Avg. Smoothness	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]	[m/s]	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]	[dB]	[dB]	[1/N]
Motive C5	2.4	0.8337	0.0019	2102.50	148.20	301.10	21.22	1552.57	140.45	24464	222.34	20.11	357	0.1719	46.8	437.43	27.84	62.64	3.99	315.84	25.92	4981	45.23	3.71	73	0.1882	93.53	84.24	0.631
NS Foam	1.0	0.8419	0.0011	2659.51	173.11	353.66	23.02	2130.54	155.63	34376	283.32	20.70	466	0.0858	50.7	572.64	32.30	76.15	4.29	405.87	28.59	5551	53.97	3.80	75	0.1429	97.27	87.59	0.615
NS Wood	2.6	0.8747	0.0013	2578.46	171.16	330.51	21.94	1816.33	148.52	29664	232.82	19.04	388	0.0991	51.2	667.64	34.47	85.58	4.42	435.09	29.20	5966	55.77	3.74	78	0.0946	102.31	92.51	0.650
Sx+	1.3	0.8350	0.0012	2540.91	173.53	316.81	21.64	1995.75	155.70	29382	248.84	19.41	373	0.0919	50.4	415.29	30.38	51.78	3.79	327.32	26.27	5955	40.81	3.28	76	0.1691	96.39	87.17	0.544
Carbon Velos	1.7	0.7866	0.0009	2421.94	157.07	309.42	20.07	1988.09	144.69	28337	254.00	18.49	369	0.0915	50.6	518.35	33.28	66.22	4.25	421.83	31.04	6416	53.89	3.97	84	0.1254	96.84	87.28	0.545
MXT-10 Foam	1.1	0.8416	0.0029	2750.79	171.56	316.38	19.73	1796.41	148.97	28703	206.61	17.13	337	0.1000	51.7	557.41	35.18	64.11	4.05	437.18	32.70	6518	50.28	3.76	76	0.1492	96.55	87.49	0.518
MXT-10 Wood	3.9	0.8859	0.0027	2721.04	172.14	296.46	18.75	1839.33	147.30	27100	200.40	16.05	301	0.0896	52.6	559.10	38.35	60.91	4.18	464.80	36.04	8022	50.64	3.93	89	0.1391	96.81	87.62	0.518
Axia ILF	2.8	0.8389	0.0030	2670.63	157.24	289.53	17.05	1734.59	142.99	28784	188.05	15.50	318	0.1207	51.3	503.71	32.01	54.61	3.47	414.22	30.40	5673	44.91	3.30	63	0.1535	95.14	85.92	0.483
Axia Formula	2.2	0.8819	0.0026	2640.09	154.50	274.61	16.07	1995.53	137.57	25476	207.57	14.31	270	0.0975	52.7	540.32	35.10	56.20	3.65	467.52	32.94	6667	48.63	3.43	71	0.1271	95.64	86.19	0.484
r		0.53	0.43	0.01	-0.20	-0.54	-0.44	-0.47	-0.47	-0.49	-0.63	-0.47	-0.56	0.21	0.18	0.17	0.39	-0.09	-0.08	0.32	0.45	0.46	0.00	0.10	0.20	-0.16	0.03	0.05	-0.15
$V = r^2$		0.2798	0.1844	0.0001	0.0387	0.2883	0.1978	0.2248	0.2188	0.2449	0.4004	0.2234	0.3118	0.0421	0.0315	0.0302	0.1496	0.0077	0.0058	0.1019	0.2068	0.2095	0.0000	0.0092	0.0405	0.0247	0.0010	0.0021	0.0216

				Position 1		Position 1 [(m/s^2) / Nm]		Position 1 Filter at 500 Hz			Position 1 [(m/s^2) / Nm]			Position 1 Decay	Speed	Position 3		Position 3 [(m/s^2) / Nm]		Position 3 Filter at 500 Hz				Position 3 [(m/s^2) / Nm]			Position 3 Decay	Max Peak	SPL	Leq/Poundage
	q	Avg. Stiffness	Avg. Smoothness	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]	[m/s]	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]	[dB]	[dB]	[1/N]
Motive C5	0.5488	0.8337	0.0019	2102.50	148.20	301.10	21.22	1552.57	140.45	24464	222.34	20.11	357	0.1719	46.8	437.43	27.84	62.64	3.99	315.84	25.92	4981	45.23	3.71	73	0.1882	93.53	84.24	0.631
NS Foam	0.5478	0.8419	0.0011	2659.51	173.11	353.66	23.02	2130.54	155.63	34376	283.32	20.70	466	0.0858	50.7	572.64	32.30	76.15	4.29	405.87	28.59	5551	53.97	3.80	75	0.1429	97.27	87.59	0.615
NS Wood	0.5483	0.8747	0.0013	2578.46	171.16	330.51	21.94	1816.33	148.52	29664	232.82	19.04	388	0.0991	51.2	667.64	34.47	85.58	4.42	435.09	29.20	5966	55.77	3.74	78	0.0946	102.31	92.51	0.650
Sx+	0.6010	0.8350	0.0012	2540.91	173.53	316.81	21.64	1995.75	155.70	29382	248.84	19.41	373	0.0919	50.4	415.29	30.38	51.78	3.79	327.32	26.27	5955	40.81	3.28	76	0.1691	96.39	87.17	0.544
Carbon Velos	0.5587	0.7866	0.0009	2421.94	157.07	309.42	20.07	1988.09	144.69	28337	254.00	18.49	369	0.0915	50.6	518.35	33.28	66.22	4.25	421.83	31.04	6416	53.89	3.97	84	0.1254	96.84	87.28	0.545
MXT-10 Foam	0.5804	0.8416	0.0029	2750.79	171.56	316.38	19.73	1796.41	148.97	28703	206.61	17.13	337	0.1000	51.7	557.41	35.18	64.11	4.05	437.18	32.70	6518	50.28	3.76	76	0.1492	96.55	87.49	0.518
MXT-10 Wood	0.5738	0.8859	0.0027	2721.04	172.14	296.46	18.75	1839.33	147.30	27100	200.40	16.05	301	0.0896	52.6	559.10	38.35	60.91	4.18	464.80	36.04	8022	50.64	3.93	89	0.1391	96.81	87.62	0.518
Axia ILF	0.5688	0.8389	0.0030	2670.63	157.24	289.53	17.05	1734.59	142.99	28784	188.05	15.50	318	0.1207	51.3	503.71	32.01	54.61	3.47	414.22	30.40	5673	44.91	3.30	63	0.1535	95.14	85.92	0.483
Axia Formula	0.5731	0.8819	0.0026	2640.09	154.50	274.61	16.07	1995.53	137.57	25476	207.57	14.31	270	0.0975	52.7	540.32	35.10	56.20	3.65	467.52	32.94	6667	48.63	3.43	71	0.1271	95.64	86.19	0.484
r		0.07	0.31	0.38	0.32	-0.33	-0.31	0.18	0.23	-0.13	-0.28	-0.37	-0.43	-0.33	0.37	-0.46	0.15	-0.74	-0.53	-0.06	0.17	0.38	-0.64	-0.53	0.00	0.29	-0.24	-0.18	-0.66
$V = r^2$		0.0049	0.0972	0.1474	0.1014	0.1059	0.0973	0.0318	0.0529	0.0181	0.0798	0.1391	0.1842	0.1084	0.1351	0.2118	0.0228	0.5408	0.2764	0.0040	0.0276	0.1480	0.4120	0.2853	0.0000	0.0813	0.0557	0.0307	0.4354

				Position 1		Position 1 [(m/s^2) / Nm]		Position 1 Filter at 500 Hz			Position 1 [(m/s^2) / Nm]			Position 1 Decay	Speed	Position 3		Position 3 [(m/s^2) / Nm]		Position 3 Filter at 500 Hz				Position 3 [(m/s^2) / Nm]			Position 3 Decay	Max Peak	SPL	Leq/Poundage
	Shooting Efficiency	Avg. Stiffness	Avg. Smoothness	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]	[m/s]	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]	[dB]	[dB]	[1/N]
Motive C5	0.581	0.8337	0.0019	2102.50	148.20	301.10	21.22	1552.57	140.45	24464	222.34	20.11	357	0.1719	46.8	437.43	27.84	62.64	3.99	315.84	25.92	4981	45.23	3.71	73	0.1882	93.53	84.24	0.631
NS Foam	0.634	0.8419	0.0011	2659.51	173.11	353.66	23.02	2130.54	155.63	34376	283.32	20.70	466	0.0858	50.7	572.64	32.30	76.15	4.29	405.87	28.59	5551	53.97	3.80	75	0.1429	97.27	87.59	0.615
NS Wood	0.620	0.8747	0.0013	2578.46	171.16	330.51	21.94	1816.33	148.52	29664	232.82	19.04	388	0.0991	51.2	667.64	34.47	85.58	4.42	435.09	29.20	5966	55.77	3.74	78	0.0946	102.31	92.51	0.650
Sx+	0.577	0.8350	0.0012	2540.91	173.53	316.81	21.64	1995.75	155.70	29382	248.84	19.41	373	0.0919	50.4	415.29	30.38	51.78	3.79	327.32	26.27	5955	40.81	3.28	76	0.1691	96.39	87.17	0.544
Carbon Velos	0.645	0.7866	0.0009	2421.94	157.07	309.42	20.07	1988.09	144.69	28337	254.00	18.49	369	0.0915	50.6	518.35	33.28	66.22	4.25	421.83	31.04	6416	53.89	3.97	84	0.1254	96.84	87.28	0.545
MXT-10 Foam	0.626	0.8416	0.0029	2750.79	171.56	316.38	19.73	1796.41	148.97	28703	206.61	17.13	337	0.1000	51.7	557.41	35.18	64.11	4.05	437.18	32.70	6518	50.28	3.76	76	0.1492	96.55	87.49	0.518
MXT-10 Wood	0.617	0.8859	0.0027	2721.04	172.14	296.46	18.75	1839.33	147.30	27100	200.40	16.05	301	0.0896	52.6	559.10	38.35	60.91	4.18	464.80	36.04	8022	50.64	3.93	89	0.1391	96.81	87.62	0.518
Axia ILF	0.593	0.8389	0.0030	2670.63	157.24	289.53	17.05	1734.59	142.99	28784	188.05	15.50	318	0.1207	51.3	503.71	32.01	54.61	3.47	414.22	30.40	5673	44.91	3.30	63	0.1535	95.14	85.92	0.483
Axia Formula	0.589	0.8819	0.0026	2640.09	154.50	274.61	16.07	1995.53	137.57	25476	207.57	14.31	270	0.0975	52.7	540.32	35.10	56.20	3.65	467.52	32.94	6667	48.63	3.43	71	0.1271	95.64	86.19	0.484
r		-0.26	-0.31	0.31	0.36	0.52	0.28	0.39	0.29	0.52	0.39	0.18	0.41	-0.53	0.30	0.63	0.48	0.63	0.73	0.52	0.39	0.29	0.87	0.80	0.55	-0.57	0.47	0.46	0.17
$V = r^2$		0.0690	0.0967	0.0965	0.1264	0.2683	0.0767	0.1487	0.0816	0.2672	0.1525	0.0316	0.1680	0.2768	0.0895	0.3931	0.2310	0.3927	0.5401	0.2656	0.1556	0.0864	0.7547	0.6354	0.3033	0.3223	0.2237	0.2113	0.0278

				Position 1		Position 1 [(m/s^2) / Nm]		Position 1 Filter at 500 Hz			Position 1 [(m/s^2) / Nm]			Position 1 Decay	Speed	Position 3		Position 3 [(m/s^2) / Nm]		Position 3 Filter at 500 Hz				Position 3 [(m/s^2) / Nm]			Position 3 Decay	Max Peak	SPL	Leq/Poundage
	ν	Avg. Stiffness	Avg. Smoothness	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]	[m/s]	P2P	RMS	P2P	RMS	P2P	RMS	Damage	P2P	RMS	Damage	Time [s]	[dB]	[dB]	[1/N]
Motive C5	2.323	0.8337	0.0019	2102.50	148.20	301.10	21.22	1552.57	140.45	24464	222.34	20.11	357	0.1719	46.8	437.43	27.84	62.64	3.99	315.84	25.92	4981	45.23	3.71	73	0.1882	93.53	84.24	0.631
NS Foam	2.131	0.8419	0.0011	2659.51	173.11	353.66	23.02	2130.54	155.63	34376	283.32	20.70	466	0.0858	50.7	572.64	32.30	76.15	4.29	405.87	28.59	5551	53.97	3.80	75	0.1429	97.27	87.59	0.615
NS Wood	2.146	0.8747	0.0013	2578.46	171.16	330.51	21.94	1816.33	148.52	29664	232.82	19.04	388	0.0991	51.2	667.64	34.47	85.58	4.42	435.09	29.20	5966	55.77	3.74	78	0.0946	102.31	92.51	0.650
Sx+	2.141	0.8350	0.0012	2540.91	173.53	316.81	21.64	1995.75	155.70	29382	248.84	19.41	373	0.0919	50.4	415.29	30.38	51.78	3.79	327.32	26.27	5955	40.81	3.28	76	0.1691	96.39	87.17	0.544
Carbon Velos	2.154	0.7866	0.0009	2421.94	157.07	309.42	20.07	1988.09	144.69	28337	254.00	18.49	369	0.0915	50.6	518.35	33.28	66.22	4.25	421.83	31.04	6416	53.89	3.97	84	0.1254	96.84	87.28	0.545
MXT-10 Foam	2.076	0.8416	0.0029	2750.79	171.56	316.38	19.73	1796.41	148.97	28703	206.61	17.13	337	0.1000	51.7	557.41	35.18	64.11	4.05	437.18	32.70	6518	50.28	3.76	76	0.1492	96.55	87.49	0.518
MXT-10 Wood	2.060	0.8859	0.0027	2721.04	172.14	296.46	18.75	1839.33	147.30	27100	200.40	16.05	301	0.0896	52.6	559.10	38.35	60.91	4.18	464.80	36.04	8022	50.64	3.93	89	0.1391	96.81	87.62	0.518
Axia ILF	2.049	0.8389	0.0030	2670.63	157.24	289.53	17.05	1734.59	142.99	28784	188.05	15.50	318	0.1207	51.3	503.71	32.01	54.61	3.47	414.22	30.40	5673	44.91	3.30	63	0.1535	95.14	85.92	0.483
Axia Formula	2.038	0.8819	0.0026	2640.09	154.50	274.61	16.07	1995.53	137.57	25476	207.57	14.31	270	0.0975	52.7	540.32	35.10	56.20	3.65	467.52	32.94	6667	48.63	3.43	71	0.1271	95.64	86.19	0.484
r		-0.40	-0.50	-0.93	-0.37	0.26	0.61	-0.43	-0.03	-0.21	0.38	0.76	0.43	0.70	-0.96	-0.37	-0.75	0.23	0.31	-0.78	-0.73	-0.63	-0.11	0.23	0.04	0.45	-0.18	-0.21	0.75
$V = r^2$		0.1631	0.2546	0.8576	0.1344	0.0676	0.3766	0.1838	0.0009	0.0426	0.1434	0.5761	0.1866	0.4883	0.9187	0.1383	0.5576	0.0525	0.0965	0.6016	0.5370	0.4025	0.0126	0.0518	0.0015	0.1988	0.0312	0.0433	0.5629

5.5. Critical evaluation of the third paper and the methodology

Some interesting results from the paper were the capability of the archers to correctly judge the speed of the arrow launched by different limbs and their relative inability to judge the smoothness of the limbs. The first result is quite astonishing due to the speed of the arrow and the position of the archer behind the arrow. A possible explanation is that the archer does not perceive the absolute speed of the arrow but the change in speed from arrow to arrow, shot by the limbs tested in sequence. Nevertheless, this is quite an interesting finding worthy of future studies. Also interesting is the fact that there is no correlation between the limbs' preference and the speed of the arrow: while the archer is capable of appreciating the change in the speed of the arrow, this does not affect his/her appreciation of the limbs. This is another quite interesting and unexpected result.

The result about the smoothness is also quite interesting: the smoothness of the limbs is one of the selling factors of the limbs, with archers preferring the wood or the foam manufacturing technology for its superior smoothness compared to the other. The finding that the archer is not capable of perceiving the smoothness of the limbs is, again, a quite interesting finding worthy of future investigations.

The convergent mixed methods design (QUAN + QUAL approach) employed in the third study was effective in analysing the relationships between objective and subjective metrics. It is important to recognise that the success of this study is largely due to its foundation on the insights gained from the first two studies. Without the opportunity to build upon prior qualitative or quantitative analyses, implementing a convergent design approach can be significantly more challenging for new studies compared to exploratory or explanatory mixed methods designs.

Chapter 6

Conclusions

6.1. The evolution of the application of the mixed research methodology

The three published papers document the evolution of the application of the mixed research methodology to the sport of archery. The applied methodology has proven to be a powerful research tool for understanding complex problems involving design, equipment performance and athletes' perception in the sport of archery. The applied methodology is based on the study of the correlations between subjective and objective metrics, respectively the qualitative and quantitative parts of the mixed research methodology. Subjective metrics are related to the sensation of the athlete in using the sports equipment, while objective metrics are measurable quantities related to the performance of the sports equipment. The choice of the metrics is related to the design feature of interest. Although this methodology allows significant freedom in the definition of the previous quantities, the following procedure is suggested:

1. Definition of the problem

   In this phase, the researcher decides the design feature of interest and determines the various configurations that will be considered in the study. A basic understanding of the problem is required to define meaningful research questions, but it has been demonstrated that different types of problems can be analysed, from broadly defined questions ('What is the best weight distribution?'), to specific questions ('What is the effect of damping?'), to the evaluation of the impact of manufacturing technologies (limb analysis).

2. Definition of the research design approach

   In this phase, the researcher decides which design approach to use in the research: an exploratory, an explanatory, or a convergent mixed methods design. All three methods were used with success to analyse the proposed problem. The researcher also needs to decide if a longitudinal method is necessary to better follow the possible temporal evolution of the problem.

3. Definition of objective metrics

   In this phase, the researcher decides what can be measured and how it will be measured. This phase is normally constrained by the instruments available to the researcher, but the broader the spectrum of data available, the better the understanding of the problem.

4. Definition of subjective metrics

   In this phase, the researcher decides what questions will be asked of the athletes. The questionnaire is prepared. This is, in the experience of the author, the most critical phase of

the entire procedure. The questions have to be designed to help the athlete in the process of quantifying a sensation and distinguishing different aspects of a sensation. Humans are quite good at averaging different inputs, so creating a questionnaire that asks the right questions can be challenging. It is suggested that a good understanding of the analysed sport is necessary. It is also suggested to carefully plan the data acquisition to minimise the effect of external and confounding variables (for example, weather and environmental conditions).

5. Data analysis and study of the correlations

   In this phase, the researcher analyses the data relative to the objective metrics and codes the subjective metrics to allow the study of the correlations between metrics. Also in this phase, a good understanding of the analysed sport is necessary to understand the physical meaning of the correlations between subjective and objective metrics and to gain a deeper understanding of the problem.

Expanding on the fourth phase of the procedure, the definition of the subjective metrics is based on the knowledge of the researcher about the analysed sport: what can be sensed with a sufficient resolution is an experience that comes from practising the sport. If the researcher is not experienced in the sport, then it will be necessary to collaborate with an expert athlete to define a meaningful set of subjective metrics. The same problem is encountered in the creation of the questionnaire. The researcher needs to know the specific jargon of the sport to formulate questions that have the same meaning for all athletes. Questions formulated using a language non-specific to the sport will normally cause misunderstanding and, possibly, random answers from the athletes. It is also important to note that the jargon specific to a sport could use keywords with a different meaning compared to the engineering meaning of the same word. For example in the third paper, the word *smoothness* has a meaning in the archery jargon completely different from the corresponding word in mechanical engineering. The questionnaires used in the three papers to collect the subjective metrics are reported in Appendix E. It is believed that the formulation of the questions improved as experience was gained in generating and administering the questionnaires.

The applied methodology has some limitations: it is not possible to study the correlations between effects that cannot be measured or sensed. It is also not possible to study the correlations between effects that cannot be sensed with sufficient resolution by the athletes, or that cannot be separated from other sensations. All three studies have a very small statistical population, but this is typical of research based on athletes. The athlete population is normally small (more true for niche sports like archery), and then the athletes able and willing to participate in the study are just a fraction of the initial, small population. Moreover, it is very complicated to guarantee a homogeneous population: athletes do not have the same level of performance but, more importantly, they do not have the same

level of sensitivity. If it is relatively simple to guarantee a common level of performance (for example defining a common level of expertise), it is more complicated to guarantee a common level of sensitivity. As reported in the three studies, the variability of the replies among the archers is sometimes significant, meaning that the archers had different levels of sensitivity and different ways of interpreting the same sensation. Both problems, small statistical population and variability in the answers are unavoidable and accepted by the research community as normal in this type of research. In the presented studies, it would have been very interesting also to differentiate the archers by gender, age, performance, etc. Unfortunately, the small statistical population did not allow for this more selective analysis.

The application of a mixed research methodology to study a sport is not limited to the sport of archery but could be implemented for any sport where the design of sports equipment has an impact on the athletes' sensations and, subsequently, on their performance. Typical examples could be the sports of golf, racquet sports (in all their variances: tennis, table tennis, padel, badminton and squash), baseball, cricket, hockey, shooting sports, etc. Every sport will necessitate a carefully planned set of metrics (both objective and subjective), but the research methodology will remain the same irrespective of the sport under analysis.

6.2. Insights addressing the research questions

At the conclusion of this study, it is important to revisit the initial research questions to assess the answers obtained and the insights gained throughout the process.

Regarding the first question: "*Is it possible to define equipment performance measurements for the sport of archery and relate them to the design of the archery equipment?*" the answer is yes. In the three papers included in this study, the objective metrics varied according to the design of the bow, indicating that each modification in design corresponds to changes in measurable quantities that can be evaluated through appropriate tests. However, it remains the researcher's responsibility to identify and define the most relevant and accurate objective metrics for this purpose.

Regarding the second question: "*is it possible to measure the archers' sensations on shooting and relate them to the design of the archery equipment?*" the answer is also yes. As demonstrated by the study of the subjective metrics, different designs influence the sensations experienced during arrow shooting. Archers are aware of these variations and can quantify changes in their sensations corresponding to different equipment configurations. However, it remains the researcher's responsibility to formulate appropriate questions and select accurate subjective metrics to capture these sensations effectively. The variability in responses is inevitable when working with human subjects, but a carefully constructed questionnaire can help mitigate this issue.

Regarding the third question: "*is it a mixed research methodology capable of evaluating the relationship between equipment performance, archery equipment design and archers' sensations?*", the answer is also yes. The three analyses effectively demonstrate the capability of a mixed research methodology in analysing and gaining insights into this complex problem. The analysis of the correlations between subjective and objective metrics was successful in providing a deep understanding of the interconnected factors and the complex connections between metrics.

An exploratory, explanatory, and convergent mixed methods designs were used with success. The exploratory mixed methods design employed in the first study proved to be highly effective in reducing the amount of qualitative data considered in the study. It allowed for the immediate identification of the most preferred weight configurations based on the archers' feedback, while the quantitative data was primarily used to investigate the underlying reasons behind these choices. The second study employed the explanatory mixed methods design. This approach is particularly effective for guiding the selection of qualitative data, as collecting quantitative data first naturally informs and shapes the subsequent qualitative data collection. A potential risk of this approach is that the quantitative data are typically limited to the capabilities of the available testing equipment, which may lead to the omission of some essential qualitative metrics. However, this was not an issue in the second study, as it built upon the first. The subjective metrics in the second study were informed and refined based on the findings from the initial research, ensuring a comprehensive assessment. The third study effectively employed the convergent mixed methods design, which allowed for the simultaneous analysis of multiple variables and facilitated the identification of meaningful correlations between objective and subjective metrics. In the absence of a predefined sequence in selecting these metrics (whether quantitative to qualitative or vice versa), it is the researcher's responsibility to ensure that a comprehensive set of metrics is included to thoroughly investigate the problem. Without a deep understanding of the problem, there is a risk of overlooking fundamental metrics that are essential for the validity and completeness of the research.

The three proposed studies were entirely successful in addressing the initial research questions and effectively demonstrating that it is possible to analyse and establish meaningful relationships between equipment performance, archery equipment design and archers' sensations.

6.3. Final remarks

This study was successful in using a mixed research methodology to evaluate the relationships between performance, design details and user sensations in archery equipment. The three presented case studies successfully analyse three different aspects of the sport of archery and report the evolution of the methodology. In each of the presented case studies, the applied methodology was

capable of providing a deep understanding of the problem with not-so-evident correlations between metrics.

The first case study analysed the problem of the best weight distribution for barebow archery style. The problem was complex due to the vague definition of 'best' (best as considering archery accuracy? best for the archer?) and the absence of any reference literature on the subject. The second case study analysed the effect of the introduction of damping in the barebow archery style. While the measurements of the effects of damping were complex from the testing point of view but straightforward in defining the objective metrics, the problem was to evaluate if the archer could feel any difference for the various configurations and to what extent the damping changed their experience of shooting. The third case study analysed the effect on the archer of different manufacturing technologies for the production of archery limbs. The problem was complex due to the variability in the limbs (poundage, manufacturing technology and connection system) and the absence of any reference literature on the subject.

All case studies succeeded in solving the proposed problems and contributed significantly to the evolution of the application of the methodology to study these types of problems. The three case studies were published in a Sage journal, Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. 'The Journal of Sports Engineering and Technology is the peer-reviewed publication of choice for authors seeking to disseminate original research findings related to the development or application of technology in sports' [88][15].

6.4. Future studies

The three presented papers are just the first steps in studying the sport of archery. The applied methodology is perfectly suited to studying the riser (the central, rigid part of the bow) and how a change in the design can affect the archer. This problem is particularly complex due to the complexity of the riser and the multitude of design details that could make a difference. Arrows are another interesting field of research due to the complexity of the arrow movements in flight. New technologies and materials are continuously developed and offered to the archery community without any technical explanation. The applied methodology is again perfectly suited to evaluate the impact of these new technologies on the archer and his/her search for performance.

As a possible future development of these studies, more sports could be considered to evaluate if the mixed research methodology could be used as the reference methodological framework to analyse the effects of new designs on athletes' performance. Also, the three archery studies raised some very

[15] Journal Impact Factor: 1.5 / 5-Year Impact Factor: 1.1

interesting questions about what athletes can sense in practising their sport and, more generally, what a person can sense and how they sense it. Research focused on these questions would complement the presented studies and offer new points of view for future developments.

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Appendix A

The first page of the three published papers.

Original Article

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Analysis of preferred weight configuration for barebow shooting style

Francesco Pietra, Philip Loveday and Robert Reid

Abstract

The barebow archery shooting style limits the stabilisation system to weights connected to the riser, which is the central part of the bow. No scientific study is available to guide the barebow archer in the choice of the best weight configuration. In the following work, a human-centred methodology was developed to address this problem from both a scientific and user-oriented perspective. The proposed methodology is based on subjective metrics (archers' sensations using the equipment), objective metrics (measurable quantities) and precision. The study sought a correlation between the subjective and objective metrics to provide insight into the problem of configuring a bow. Eleven weight configurations were considered. The vibration was measured at five positions on the bow and the 3D dynamic motion was measured using an inertial measurement unit. Seven archers completed a questionnaire to evaluate the subjective shooting sensations. The results show that the two best weight configurations are the 250–200 g and the 350–200 g, at the central and lower attachment points, respectively. A strong correlation exists between the vibration level of the bow and the feeling archers associated with the shooting, and between the dynamic motion of the bow and the comfort of the shooting. No correlation was found between the vibration time and the physical sensations felt by the archers. Determining the influence of the weight configuration on shooting accuracy, with statistical significance, would require an impractically large number of arrows to be shot for each weight configuration. A new methodology was developed to correlate the archers' physical sensations to measurable parameters and this was applied to understand the barebow weight selection problem. This methodology could be further developed to correlate additional subjective and objective metrics. An understanding of these correlations would allow objective metrics, which can be simulated in the design process, to be used to ensure satisfaction of subjective metrics by the final design.

Keywords

Archery, barebow, barebow weight configurations, subjective metrics, objective metrics, correlation

Date received: 26 September 2022; accepted: 14 January 2023

Introduction

The World Archery Federation (WA) is the international federation for the Olympic and Paralympic sport of archery.[1] The WA recognises three styles for archery: the recurve bow – which is the style used at the Olympic games, the compound bow and the barebow style.[2] Recurve and barebow archers use the same type of bow, but in the barebow style the sight and the clicker are not allowed and the V-Bar stabilisation system of the recurve style is limited to simple weights attached to the riser (the central, rigid part of the bow).[3]

The main functions of an archery stabilising system (weights added to the bow to stabilise its motion during shooting) are control of the displacement and the rotation of the bow during the aiming phase, control of the vibrations,[4] and control of the dynamic action of the bow on string release.[5,6] This set of requirements defines the shape of the stabilisation system.

The dynamic behaviour of the bow on release is related to the weight distribution of the stabilising system (weight configuration) in comparison to the position of the centre of gravity (CoG) of the bow.

A Cartesian coordinate system is defined as centred on the pressure button[7] (Figure 1). The X axis follows

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Objective and subjective measurements of the influence of dampers on the shooting experience of barebow archers

Francesco Pietra, Philip W Loveday and Robert Reid

Abstract

The barebow archery shooting style previously limited the stabilisation system to weights connected to the riser, which is the central part of the bow, but recently the use of damping devices has been allowed. No scientific study is available to evaluate the effect of damping on the archers' shooting experience. A human-centred methodology was developed to address this problem. Objective metrics (measurable quantities) and subjective metrics (archers' sensations using the equipment) were defined. These metrics were correlated to obtain a deeper understanding of the problem. Fifty-one weight configurations were tested for mechanical vibrations and sound of the bow on shooting. The mechanical vibration was measured at five positions on the bow. Fifteen configurations were selected and tested by eight archers to evaluate the subjective metrics. The results show that dedicated vibration-damping devices are capable of significantly reducing the mechanical vibrations and the intensity and pitch of the sound of the bow on shooting. A strong correlation exists between reduced vibrations, lower intensity and pitch* of the sound of the bow and the quality of the shooting experience. The methodology used in this work was successful in fostering an understanding of the relationship between objective and subjective metrics on shooting. The results of this analysis could be used to improve existing designs or create new products for archery.

Keywords

Archery, barebow, barebow weight configurations, damping, subjective metrics, objective metrics, bow vibrations, bow sound, correlation, archer's experience, World Archery

Date received: 19 May 2023; accepted: 18 October 2023

Introduction

World Archery (WA) is the international federation responsible for the Olympic and Paralympic sport of archery. WA also organises international events, including a world championship,[1] for the three archery styles: compound, recurve and barebow. Recurve and barebow archers use the same type of bow, but in the barebow style use of the sight and the clicker are not allowed and the V-Bar stabilisation system of the recurve style is limited to simple weights attached to the riser (the central, rigid part of the bow).[2]

The main functions of a stabilising system (weights added to the bow to stabilise its motion during shooting) are the control of the movement of the bow during the aiming phase, the control of vibrations,[3] and control of the dynamic action of the bow on string release.[4,5]

The dynamic behaviour of the bow on release is related to the weight configuration in comparison to the position of the centre of gravity (CoG) of the bow. A Cartesian coordinate system is defined as centred on the pressure button[6] (Figure 1). The X axis follows the direction of the arrow, parallel to the ground. The Y axis lies in the plane of the bow (the plane created by the string and the middle section of the limbs), upward.

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Investigation into the correlations between engineering measurements and archers' perceptions of different limbs in a recurve bow

Francesco Pietra, Philip W Loveday and Robert Reid

Abstract

A novel methodology was developed to correlate the performance of different sets of archery limbs, chosen from different manufacturers, manufacturing technologies and connection systems, to the sensations experienced by the archers using the bow. Objective metrics (measurable quantities) and subjective metrics (archers' sensations while using the equipment) were defined. These metrics were correlated to obtain a deeper understanding of the relationship between the metrics. Nine sets of limbs were tested to determine their static loading curve, speed of arrows on release, mechanical vibrations and sound of the bow on shooting. The mechanical vibrations were measured at two positions on the bow. The limbs were tested by ten archers to evaluate the subjective metrics. Three quality coefficients were used that related to engineering measurements. These quality coefficients could be used to evaluate the relative performance of the limbs. The analysis of the correlations between objective and subjective metrics provides new insights into the problem, highlighting interesting relationships between engineering measurements and archers' sensations. The methodology used in this work was successful in fostering an understanding of the relationship between objective and subjective metrics on shooting. The results of this analysis could be used to improve existing designs or create new products for archery.

Keywords

Archery, archery limbs selection, subjective metrics, objective metrics, bow vibrations, bow sound, correlation, archer's experience

Date received: 16 January 2024; accepted: 13 May 2024

Introduction

The first scientific studies of archery were conducted in 1937[1] and 1943.[2] The insight gained from these early studies questioned the traditional English longbow design and initiated the process that would create the Olympic recurve bow. The Olympic recurve bow design is a hybrid between the English longbow and the traditional recurve bow (Turkish bow): while the tips of the limbs resemble the traditional recurve bow being initially bent in the opposite direction of the draw, the Olympic recurve bow is longer than the traditional recurve bow and similar in size to the longbow.[3] The modern Olympic recurve consists of a central rigid part called the 'riser', two flexible parts called 'limbs' and a string to connect the two tips of the limbs (Figure 1). The arrow is connected to the string and is supported by the arrow rests attached to the riser (Figure 2).

The action of shooting the arrow comprises the following steps: the archer pulls the string from the rest position (brace height) to the maximum draw (full draw) deforming the limbs in the process. The string is released and the arrow accelerates leaving the string and the bow. The limbs are the only mechanism in the bow responsible for storing the potential energy caused by the deformation imposed by the draw of the arrow. The string is essentially inextensible and does not

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Appendix B

A short historical excursus on the evolution of the bow

Pre 25,000 BC

The discovery of the first stone arrowheads in Africa tends to indicate that the bow and arrow were invented there, maybe as early as 50,000 BC and it was probably developed in conjunction with the invention of the spear thrower (*atlas*) [15] [89].

5,000 – 18,000 BC

Fire-hardened points were used as the tips of the arrows. Successively, flint arrowheads were shaped to a point, inserted into a slot and tied with sinew to the front of the arrow. Feathers were glued and tied with sinew to the arrow shafts [15].

9,000 – 6,000 BC

Bows were found in Denmark that date from approximately 8,000 – 6,000 BC. These bows are selfbows (made with one piece of wood) made from yew or elm and are 'tillered' (the limbs are thinned to guarantee an even amount of bend on top and bottom limbs) [16] [17].

3,300 BC

A 45-year-old man died on the Similaun Glacier with a flint arrowhead embedded in his left shoulder. His preserved body was found on the 11th of September 1991. He had a quiver containing 14 arrows, a flint dagger, a copper axe and an unfinished bow stave [90] [91] [92].

2,800 BC

The Composite Bow first appears. The Egyptians further developed this type of bow (Figure 13). Made from wood, tipped with animal horn and held together with animal sinew and glue. The unstrung bow resembled a 'C' shape and required two people to string it. The bowstrings were made from 'catgut' obtained and made from sheep's intestines. The arrows were extremely light and when used with the composite bow, could be shot 366 metres (400 yards) and the armour of the day was no protection against such weapons. The Egyptians used archers on the back of light chariots. These were organised into highly trained units able to quickly out-flank an enemy army with devastating effect [15] [22].

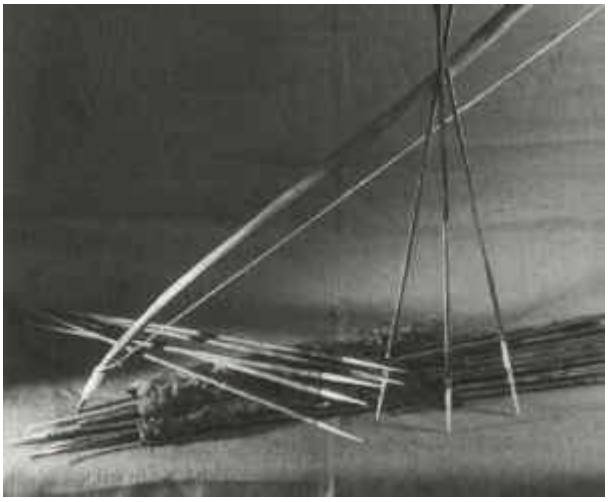


Figure 17 - 2300 -1400 BC – Egyptian bow and arrows. Bow length = 62"-68" (160-173 cm). Arrows made from reeds with hard foreshafts 8" (20 cm) long bound into the shaft with very fine linen thread and then tipped with flint heads. The fletchings are 3" (7.5 cm) long feathers glued to the shafts with shellac. Arrow length = 34"-37" (86-94 cm). Arrow weight = 0.4-0.5 oz (10-14 g) [15].

1,500 – 1027 BC

The first mention of Crossbows in China.

490 BC

'Battle of Marathon', Athenian infantry of 11,000 men with long spears, swords and armour defeated Persian archers after a rapid charge to avoid the shower of arrows. The Persian army of 15,000 men was flanked by the infantry and lost 6,400 men killed in retreat back to their ships. The Athenians only lost 192 men. According to legend, an Athenian messenger was sent from Marathon to Athens, a distance of about 40 km (25 miles), and there he announced the Persian defeat before dying of exhaustion [15] [93].

500 AD

Introduction of the bow in North America [94].

434 AD

Attila the Hun reigned as King from 434 to 453 AD. The Huns used composite recurve bows from horseback with deadly effects on opposing armies. The Hun kingdom was located in modern-day Hungary. Attila embarked upon a series of wars extending Hun rule from the Rhine across the north of the Black Sea as far as the Caspian Sea. Some historical accounts number his army between 300,000 to 700,000 troops. The defeat of his army by the allied Roman and Visigoth armies at Chalons in 451 AD thwarted his first campaign into Western Europe. The following year, he invaded Northern Italy, nearly securing Ravenna, but halted at the request of Pope Leo I and returned home to his capital near present-day Budapest. He died in 453 AD, supposedly choking to death on a nosebleed while in a drunken stupor after marrying another wife.

300 AD

The Magyar (Hungarian) people, a brother tribe to the Huns, made and used composite recurve bows (Figure 14). They were excellent at using these bows on horseback [15] [95].



Figure 18 - 300 AD – An example of a Magyar (Hungarian) composite recurve bow. Graphical reconstruction of the Niya Bow by Stephen Selby (from the original on display in the Revolutionary Museum in Beijing, China). Bow: Length: 130 cm. Width: 0.6 cm – 3.2 cm. Thickness: 0.6 cm – 4.6 cm. Arrow: Length: 73.5 cm [15].

1066 AD

The Battle of Hastings – King Harold of England was waiting for the invasion by William of Normandy. His army was lined up along a ridge line forming a 'shield wall' battle tactic as he was waiting for more of his troops to arrive from an earlier battle against Vikings further north. William's army had the disadvantage of attacking uphill. His archers tried shooting at the shield wall, but their arrows were stopped by the troops' shields or flew overhead due to shooting uphill. William changed tactics and ordered his archers to aim high and thus lob their arrows onto Harold's troops. This 'rain' of arrows decimated the army and allowed the foot soldiers to break through the shield wall. It is believed that King Harold was killed by an arrow through the eye (Figure 15), which resulted in victory for William [15].



Figure 19 - 1066 AD – Part of the Bayeux Tapestry showing King Harold struck by the arrow [15].

The Battle of Hastings is recorded as the first time the English longbow appeared in a battle. This recording is somewhat imprecise: Hasting is the first battle where a significant number of archers were used to win a battle. The longbow was not invented by the English (as an evolution of the shortbow) but was already developed when Hastings happened [96] [97] [98]. The victory of William of Normandy had a very important consequence: all English weapons were confiscated but the longbows, considered an inferior weapon not suited for war. As a consequence, the longbow became the weapon of the English freemen, starting a tradition that would last for three centuries [13].

1099 AD

Crusades. English knights and crossbowmen attacked the Mohammedan army, which mainly consisted of archers on horses armed with composite bows [22] [99] [100].

1100 – 1135 AD

Henry I of England proclaimed that an archer would be absolved of murder if he killed a man during archery practice, but only if he had first shouted "Fast" (meaning stand fast – or in modern language "to stay still") as a warning to anyone straying nearby [15].

1189 – 1192 AD

Crusades. King Richard was killed with a crossbow bolt shot by a defender using one of the attacking army's crossbow bolts. The bolt didn't kill Richard outright, but the wound became infected because it was impossible to remove the arrowhead from the shoulder.

1208 AD

Temujin became the Great Khan of the Mongols, better known as Genghis Khan. The Mongols were expert mounted archers who used high stirrups which allowed them to shoot in any direction. They used composite bows (70 – 160 lb draw weight) and released the bowstring with a thumb ring that increased the killing range of the bow to 275 metres (300 yards). The maximum range of their bows was about 550 metres (600 yards) [15].

1333 AD – 19th July

Battle of Halidon Hill. The Scottish army was defeated by Edward III of England demonstrating for the first time the full potential of the English Longbow in battle (22,000 Scottish heavy cavalry defeated by 2,000 English archers and 500 knights).

1346 AD – 26th August

Battle of Crecy. Edward III of England leads his army against the French. The French force of crossbowmen attacked from the front but they were routed by the English archers (Figure 16). The French cavalry then charged, but was decimated by the English archers. 1,542 French knights were killed with only 50 English killed [13] [101].



Figure 20 - 1346 AD, Battle of Cresy – French crossbowmen shown on the left using 'cranks' to pull the bowstring back while the English longbowmen on the right showered them with arrows [15].

1356 AD – 19th September

'Battle of Poitiers' – Edward III of England defeats King John II of France. The English troops took up positions on marshy ground near a river and when the French knights charged, they became bogged and easy targets for the English archers. King John is taken prisoner and held in the Tower of London. A ransom of 3,000,000 gold crowns is demanded for his release [13] [101].

1415 AD – 25th October

Battle of Agincourt (Figure 17): Henry V of England was leading his army back to Calais in France after a successful campaign to the south. At the village of Agincourt, Henry and his army were confronted by a French army camped to the North. Henry's army consisted of 1,500 men-at-arms and 5,500 archers. The French army consisted mainly of noble knights on foot and cavalry, some 23,000 in total. Henry arranged his army at the narrow end of the battlefield with archers on each flank. The French army was arranged on the much wider end of the battlefield with the cavalry on each flank. The French Nobles disregarded the battle plan ordered by the French King and ordered the cavalry to charge the archers. The French noble cavalry were probably wearing expensive steel armour which protected them against the iron bodkin tips of the arrows (Figure 18), except that their horses were not as well protected. Most of the horses were probably killed or wounded in the first few minutes of the battle. The rest of the French army followed the cavalry charge and were obstructed by fleeing or dead horses, plus the narrowing of the battlefield, which led to mass chaos. The battle lasted about two hours, … Some accounts state as many as 10,000 French soldiers were killed, with only 100 English soldiers killed [13] [101].



Figure 21 - 1415 – The Battle of Agincourt shows longbowmen to the front with knights behind [15].

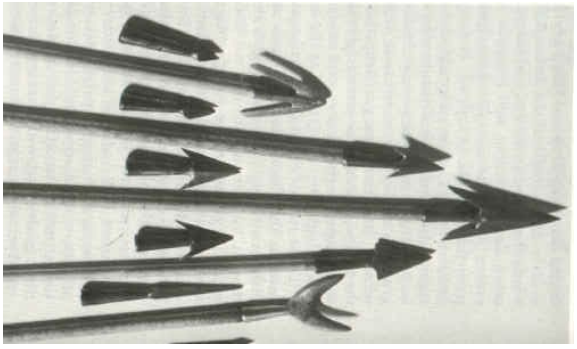


Figure 22 - Examples of types of arrow tips used in the 15th century. The 'barbed' arrow tips were the most commonly used. The small triangular tips without 'barbs', Bodkin's, were used to pierce the chainmail armour. The 'half-moon' arrow tips were used to shoot through the sails of opposing ships [15].

1500 – 1550 AD

Ballads about Robin Hood are circulated: "Lyttell Geste of Robyn Hode", 'Robin and the Knight', 'Robin, Little John and the Sheriff', 'Robin and the King' and 'Robin Hood's Death' [102].

1520 AD

The musket was invented.

1521 AD

General Cortes of Spain used crossbowmen in his conquest of Mexico.

1534 AD

King Henry ordered that 30,000 bows be made and kept at the Tower of London.

1545 AD

King Henry's flagship "Mary Rose" sinks in the Solent near Portsmouth, England. The remains were recovered in 1982 from the fine silt that has preserved the hull and its contents. Over 100 longbows were found, all made from fine-grained yew [103].

1588 AD

10,000 soldiers on the English fleet, armed with muskets, defeated the Spanish Armada.

1595 AD

In England, all bows were ordered to be exchanged for muskets. The long training period of the archer and not the performance of the bow was the main reason for the substitution of the longbow with firearms. The starting training age for an English bowman in the Middle Ages was six years of age and he was accepted into the army at around 20 years of age [16]. The training time with a firearm was, in the 17th century, a couple of months and no particular physical requirements were requested to fire a matchlock or, later, a musket.

In other countries, the bow will remain in use for a longer period. For example, the Muscovite cavalry replaced the composite reflex bow with firearms only in the 17th century. The reason for this was that the firearms were impossible to reload on a moving horse so, if the bow lacked stopping power, it still had a better volume of fire compared to the firearms [104].

1644 AD

Tipper Muir was the last battle in which English archers were used against a Scottish army [15].

1700 – Present Day

In the 1780s the English longbow enjoyed a renaissance, as historical archery became a fashionable recreation among the English aristocracy. Later, during 1819–1845, longbow archery developed into a mass movement, as it spread downwards in the English class system, into the bourgeoning middle class [26] [27].

1900 – Archery in the Olympic Games. Archery was also present in the Olympic Games in 1904, 1908 and 1920. Women were allowed to compete in the Archery event in 1904 and 1908 (Figure 19).



Figure 23 - 1908 – Ladies competing in the 1908 Olympics with longbows [15].

1931 – FITA (Fédération Internationale de Tir à l'Arc), which is the French name for the World Archery Federation (WA) is formed.

1942 – Hoyt Archery Co. was started by Earl Hoyt Jr.

1946 – Easton's first trademarked aluminium arrows "24 SRT-X" produced.

1951 – Max Hamilton introduced 'Plastiflech' vanes to replace feathers. The British Long-Bow Society was formed to preserve the traditional recreational longbow and style of shooting (two-way) as modern steel bows (and later composites) along with one-way shooting, threatened to remove this historic bow from the archery scene. Now has well over 2,000 members in several countries.

1953 – **'**Bear' designs and the sale of the first working recurve bow.

1958 – Easton develops "XX75" aluminium arrow.

1961 – **'**Torque Stabilisers' introduced by Hoyt Archery Co.

1966 – Easton develops "X7" aluminium arrow. IFAA (International Field Archery Association) was founded.

1969 – 30th December – Holless Wilbur Allen is granted the patent on his invention of the Compound Bow, which he had designed 3 to 4 years earlier. His original design had 'wheels' that were triangular-shaped.

1983 – Easton develops the carbon arrow.

1990 – The Olympic Round elimination format was adopted at the Olympic Games to increase public interest.

2003 – Win & Win Archery Co. of Seoul, Korea released composite carbon & aluminium recurve bow riser and composite titanium & carbon recurve bow limbs.

2008 – Developments in materials technology will see the production of lighter and stronger bows as well as lighter and stronger arrows. Arrow speed will increase, giving better accuracy over longer distances.

Appendix C

Google Scholar database, accessed on the 19th of May 2025.

Keywords: +archery +bow +design +performance

9,390 results. The first 20 results are reported and analysed in detail.

1. Design and materials in archery
   BW Kooi - Materials in Sports Equipment, 2019 – Elsevier
   Mathematical modelling of the limbs for mechanical performance. Not relevant to the problem analysed in the thesis.
2. Designing a better archery bow
   C Ledsome - … Conference on Engineering and Product Design …, 2018 - designsociety.org
   List of requested performances for the archery bow. Not relevant to the problem analysed in the thesis.
3. Optimization of Bow and Arrow Design Subject to Aerodynamic Characteristics
   MKFM Azizi, SJMM Saleh… - Journal of Aviation and …, 2019 - jaat.fazpublishing.com
   Optimisation of arrow design. Not relevant to the problem analysed in the thesis.
4. [PDF] Archery and mathematical modelling
   BW Kooi - Journal of the Society of Archer-Antiquaries, 1991 - bio.vu.nl
   Mathematical modelling of the limbs for mechanical performance. Not relevant to the problem analysed in the thesis.
5. Improving the arrow selection process in archery: the stiffness variation pattern matters
   A Kuch, P Laguillaumie, F Durand, JF Debril… - Sports Engineering, 2025 – Springer
   Selection of arrows for performance. Not relevant to the problem analysed in the thesis.
6. [BOOK] Archery Anatomy: An introduction to techniques for improved performance
   R Axford - 2017 - books.google.com
   Archery shooting technique in relation to the archer's anatomy. Not relevant to the problem analysed in the thesis.
7. [HTML] Optimisation of design parameters for Turkish Tirkeş (war) bow
   S Demir, B Ekici - Composites Part B: Engineering, 2014 – Elsevier
   Optimisation of the design of the composite Turkish bow. Not relevant to the problem analysed in the thesis.
8. [BOOK] Archery: Steps to success
   K Haywood, C Lewis - 2024 - books.google.com
   Archery manual. Not relevant to the problem analysed in the thesis.
9. Mechanics of the modern target archery bow and arrow
   SH Joseph, S Stewart - Proceedings of the 1996 1st International …, 1996 - books.google.com
   Introduction of a modern bow for recurve archery. Not relevant to the problem analysed in the thesis.
10. Investigation into the correlations between engineering measurements and archers' perceptions of different limbs in a recurve bow
    F Pietra, PW Loveday, R Reid - Proceedings of the Institution …, 2024 - journals.sagepub.com
    The third paper of this thesis.
11. Performance assessment in archery: a systematic review
    E Vendrame, V Belluscio, L Truppa, L Rum… - Sports …, 2024 - Taylor & Francis
    Analysis of physiological and kinematic parameters in the sport of archery. Not relevant to the problem analysed in the thesis.

12. Testing and Tuning of the Sport Archery Bow and Arrow System
    I Zanevskyy, L Zanevska - International Journal of Sport Culture and …, 2023 - dergipark.org.tr
    Analysis of how tuning of the bow increases performance in the sport of archery. Not relevant to the problem analysed in the thesis.
13. Archery bow grip force distribution: relationships with performance and fatigue
    PE Martin, GD Heise - Journal of Applied …, 1992 - journals.humankinetics.com
    Analysis of the shooting technique. Not relevant to the problem analysed in the thesis.
14. Performance archery shooting
    H Sabers - 2019 - search.proquest.com
    Analysis of the shooting technique. Not relevant to the problem analysed in the thesis.
15. Using group sizes to optimise archery equipment
    JL Park - Proceedings of the Institution of Mechanical …, 2023 - journals.sagepub.com
    The paper is cited in the thesis. Not relevant to the problem of the relationship between design and performance analysed in the thesis.
16. Archery bow design equation
    R Verma - European Journal of Engineering and Technology …, 2020 - ej-eng.org
    Analysis of how arrow mass, energy stored in the bow, and energy transferred to the arrow relate to performance. Not relevant to the problem analysed in the thesis.
17. [BOOK] Archery fundamentals
    T Johnson - 2014 - books.google.com
    Archery manual. Not relevant to the problem analysed in the thesis.
18. [PDF] Alternative design for the compound archery bow
    DL Griffith - 1992 - dspace.mit.edu
    Compound bow. Not relevant to the problem analysed in the thesis.
19. [PDF] Development and analysis of arrow for archery
    WF Yong, Z Ahmad, IM Sahat - ARPN Journal of Engineering and …, 2016 - researchgate.net
    Design of arrows for performance. Not relevant to the problem analysed in the thesis.
20. Standardised equipment or specialist groups? The role of archery aboard Mary Rose
    AC Parkes - 2024 - eprints.soton.ac.uk
    Historical paper. Not relevant to the problem analysed in the thesis.

    The next 30 results were analysed with no results relevant to the problem analysed in the thesis.

Keywords: "performance in archery"

529 results. The first 20 results are reported and analysed in detail.

1. Emotions, heart rate and performance in archery: A case study
   C Robazza, L Bortoli, V Nougier - Journal of Sports Medicine …, 1999 - search.proquest.com
   Medical paper. Not relevant to the problem analysed in the thesis.
2. Assessment of target performance in archery
   İE Kolayis, M Çilli, H Ertan, JA Knicker - Procedia-Social and Behavioral …, 2014 – Elsevier
   Performance paper based on the score on target. Not relevant to the problem analysed in the thesis.

3. Performance assessment in archery: a systematic review
   E Vendrame, V Belluscio, L Truppa, L Rum… - Sports …, 2024 - Taylor & Francis
   Analysis of physiological and kinematic parameters in the sport of archery. Not relevant to the problem analysed in the thesis.
4. A multivariate analysis of cardiopulmonary parameters in archery performance
   V Eswaramoorthi, MR Abdullah, RM Musa… - Human …, 2018 - termedia.pl
   Medical paper. Not relevant to the problem analysed in the thesis.
5. Comparative analysis of the correlation between anxiety, salivary alpha amylase, cortisol levels, and athletes' performance in archery competitions
   IS Lim - Journal of exercise nutrition & biochemistry, 2018 - pmc.ncbi.nlm.nih.gov
   Medical paper. Not relevant to the problem analysed in the thesis.
6. The perception of elite athletes' guided self-reflection and performance in archery
   SL Tan, KT Koh, M Kokkonen - Reflective Practice, 2016 - Taylor & Francis
   Psychological paper. Not relevant to the problem analysed in the thesis.
7. Psychological relatedness factor influencing performance in archery
   IHA Samah, AS Shamsudin… - International Journal of …, 2019 - journals.tultech.eu
   Psychological paper. Not relevant to the problem analysed in the thesis.
8. Shooting performance in archery: a perspective of dynamic–static balance
   İ Kesilmiş, F Söğüt, Ü Çömelekoğlu - Sport sciences for health, 2024 – Springer
   Analysis of the shooting technique. Not relevant to the problem analysed in the thesis.
9. Psychological aspects of archery
   KM Haywood - The Sport Psychologist's Handbook: A Guide for …, 2006 - Wiley Online Library
   Psychological paper. Not relevant to the problem analysed in the thesis.
10. The effect of fatigue and elevated heart rate on archery shot performance
    B Higginson - International Journal of Exercise Science …, 2016 - digitalcommons.wku.edu
    Analysis of the shooting technique. Not relevant to the problem analysed in the thesis.
11. The effect of self-efficacy, social support, and achievement motivation on archery athlete's performance
    MSR Wibowo - Retos: nuevas tendencias en educación física …, 2024 - dialnet.unirioja.es
    Psychological paper. Not relevant to the problem analysed in the thesis.
12. [HTML] Improving physical function by focusing on sports archery training
    J Geng, J Wang, T Wang, X Yan - Revista Brasileira de Medicina do …, 2023 - SciELO Brasil
    Psychological paper. Not relevant to the problem analysed in the thesis.
13. Physiological arousal and performance in elite archers: A field study
    C Robazza, L Bortoli, V Nougier - European psychologist, 1998 - econtent.hogrefe.com
    Psychological paper. Not relevant to the problem analysed in the thesis.
14. Effects on archery performance of manipulating metamotivational state and felt arousal
    JH Kerr, H Yoshida, C Hirata, K Takai… - … and Motor skills, 1997 - journals.sagepub.com
    Psychological paper. Not relevant to the problem analysed in the thesis.
15. Bio-physiological indicators in evaluating archery performance
    R Muazu Musa, Z Taha, A PP Abdul Majeed… - Machine Learning in …, 2019 – Springer
    Medical paper. Not relevant to the problem analysed in the thesis.
16. Results of beginner archery skills among adolescents based on gender review and shot distance
    D Destriani, H Yusfi, D Destriana… - … en educación física …, 2024 - dialnet.unirioja.es
    Performance paper based on the score on target. Not relevant to the problem analysed in the thesis.

17. Physical capacity and performance correlation in sub-elite Indonesian archery athletes
    A Rusdiawan, DA Kusuma, MLSA Rasyid… - … en educación física …, 2024 - dialnet.unirioja.es
    Medical paper. Not relevant to the problem analysed in the thesis.
18. [HTML] Effects of dehydration on archery performance, subjective feelings and heart rate during a competition simulation
    A Savvides, C D. Giannaki, A Vlahoyiannis… - Journal of functional …, 2020 - mdpi.com
    Medical paper. Not relevant to the problem analysed in the thesis.
19. [PDF] Heart rate values during shooting is a field-side performance analysis tool in archery-a study of elite indian archers
    CS Guru, A Krishnan, U Mahajan… - International journal of …, 2020 - academia.edu
    Medical paper. Not relevant to the problem analysed in the thesis.
20. [PDF] A monitoring of archery performance predictors among state-level archers
    LJ Sien - 2023 - eprints.usm.my
    Medical paper. Not relevant to the problem analysed in the thesis.

    The next 30 results were analysed with no results relevant to the problem analysed in the thesis.

Appendix D

Ethic Clearance from the University of the Witwatersrand

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Research Office

HUMAN RESEARCH ETHICS COMMITTEE (NON-MEDICAL)
R14/49 Pietra

CLEARANCE CERTIFICATE	**PROTOCOL NUMBER: H22/01/25**
PROJECT TITLE	Performance Evaluation and Optimisation of the Olympic Recurve Riser
INVESTIGATOR(S)	Mr F Pietra
SCHOOL/DEPARTMENT	Mechanical, Industrial and Aeronautical Engineering/
DATE CONSIDERED	28 January 2022
DECISION OF THE COMMITTEE	Approved Risk Level: Minimal
EXPIRY DATE	07 March 2025

DATE 08 March 2022 **CHAIRPERSON** _____
(Professor J Watermeyer)

cc: Supervisor : Prof P Loveday and Prof R Reid

DECLARATION OF INVESTIGATOR(S)

To be completed in duplicate and **ONE COPY** returned to the Secretary at Room 10004, 10th Floor, Senate House, University. Unreported changes to the application may invalidate the clearance given by the HREC (Non-Medical)

I/We fully understand the conditions under which I am/we are authorized to carry out the abovementioned research and I/we guarantee to ensure compliance with these conditions. Should any departure to be contemplated from the research procedure as approved I/we undertake to submit an amendment of the protocol to the Committee. **I agree to completion of a regular progress report. For Minimal and Low studies, this is due annually on 31 December. For Medium and High Risk studies, this is due twice annually on 30 June and 31 December.**

Francesco Pietra
Signature

09 / 03 / 2022
Date

PLEASE QUOTE THE PROTOCOL NUMBER ON ALL ENQUIRIES

Appendix E

Questionnaire from the First Paper

1. Weight balance of the bow during the drawing and aiming phases

Procedure

- The bow is prepared without the archer knowing the weight configuration used in the test
- The instructions are read, explained and any question is answered
- The test results are recorded

Instructions

Please score the following weight configurations rating the feeling associated with the draw of the string and the aiming to the target. The rating goes from 1, very bad feelings, to 5 very good feelings. You are suggested to not shoot the arrow, but just to focus on the weight balance of the bow during the drawing and the aiming phases, and how the specific weight configuration changes the feel of the draw and the aim.

Scoring table

Weight configuration	Very Bad [1]	Bad [2]	Acceptable [3]	Good [4]	Very Good [5]
Naked	☐	☐	☐	☐	☐
200-0	☐	☐	☐	☐	☐
200-250	☐	☐	☐	☐	☐
200-350	☐	☐	☐	☐	☐
250-0	☐	☐	☐	☐	☐
250-200	☐	☐	☐	☐	☐
250-350	☐	☐	☐	☐	☐
350-0	☐	☐	☐	☐	☐
350-200	☐	☐	☐	☐	☐
350-250	☐	☐	☐	☐	☐
V-Bar	☐	☐	☐	☐	☐

2. Vibrations of the bow

Procedure

- The bow is prepared without the archer knowing the weight configuration used in the test
- The instructions are read, explained and any question is answered
- The test results are recorded

Instructions

Please score the following weight configurations by rating the vibrations level associated with the shooting of the arrow. The rating goes from 1, a very high vibration level, to 5 a very low vibration level. You are requested to focus just on the vibration level during the shooting, trying to ignore all the other components of the shooting.

Scoring table

Weight configuration	Very High [1]	High [2]	Acceptable [3]	Low [4]	Very Low [5]
Naked	☐	☐	☐	☐	☐
200-0	☐	☐	☐	☐	☐
200-250	☐	☐	☐	☐	☐
200-350	☐	☐	☐	☐	☐
250-0	☐	☐	☐	☐	☐
250-200	☐	☐	☐	☐	☐
250-350	☐	☐	☐	☐	☐
350-0	☐	☐	☐	☐	☐
350-200	☐	☐	☐	☐	☐
350-250	☐	☐	☐	☐	☐
V-Bar	☐	☐	☐	☐	☐

3. Dynamic behaviour of the bow

Procedure

- The bow is prepared without the archer knowing the weight configuration used in the test
- The instructions are read, explained and any question is answered
- The test results are recorded

Instructions

Please score the following weight configurations rating the dynamic behaviour of the bow associated with the shooting of the arrow. The rating goes from 1, very bad behaviour, to 5 very good behaviour. You are requested to focus just on the dynamic behaviour of the bow at the end of the shooting, trying to ignore all the other components of the shooting.

Scoring table

Weight configuration	Very Bad [1]	Bad [2]	Acceptable [3]	Good [4]	Very Good [5]
Naked	☐	☐	☐	☐	☐
200-0	☐	☐	☐	☐	☐
200-250	☐	☐	☐	☐	☐
200-350	☐	☐	☐	☐	☐
250-0	☐	☐	☐	☐	☐
250-200	☐	☐	☐	☐	☐
250-350	☐	☐	☐	☐	☐
350-0	☐	☐	☐	☐	☐
350-200	☐	☐	☐	☐	☐
350-250	☐	☐	☐	☐	☐
V-Bar	☐	☐	☐	☐	☐

Questionnaire from the Second Paper

1. Vibrations of the bow

Procedure

- The bow is prepared without the archer knowing the weight configuration used in the test
- The instructions are read, explained and any question is answered
- The archer wears earplugs to eliminate/reduce the sound of the bow
- The test results are recorded

Instructions

Please score the following weight configurations rating the vibration level associated with the shooting of the arrow. The rating goes from 1, a very high vibration level, to 5 a very low vibration level. You are suggested to focus just on the vibration level during the shooting, trying to ignore all the other components of the shooting (primarily the sound of the bow).

Scoring table

Weight configuration	Very High Vibrations [1]	High Vibrations [2]	Acceptable Vibrations [3]	Low Vibrations [4]	Very Low Vibrations [5]
XXX-YYY (B)	Reference configurations				
200-250 (A)	☐	☐	☐	☐	☐
200-250 (D)	☐	☐	☐	☐	☐
200-250 (E)	☐	☐	☐	☐	☐
250-200 (A)	☐	☐	☐	☐	☐
250-200 (D)	☐	☐	☐	☐	☐
250-200 (E)	☐	☐	☐	☐	☐
350-0 (A)	☐	☐	☐	☐	☐
350-0 (C)	☐	☐	☐	☐	☐
350-0 (E)	☐	☐	☐	☐	☐
350-200 (A)	☐	☐	☐	☐	☐
350-200 (D)	☐	☐	☐	☐	☐
350-200 (E)	☐	☐	☐	☐	☐
350-250 (A)	☐	☐	☐	☐	☐
350-250 (D)	☐	☐	☐	☐	☐
350-250 (E)	☐	☐	☐	☐	☐

2. Sound of the bow during the shooting

Sound Level

Procedure

- The bow is prepared without the tester knowing the weight configuration used in the test
- The instructions are read, explained and any question is answered
- The tester stays next to the bow while the archer is shooting the arrow
- The test results are recorded

Instructions

Please score the following weight configurations rating the sound level associated with the shooting of the arrow. The rating goes from 1, a very high-intensity sound (noisy bow), to 5 a low-intensity sound (quiet bow). You are suggested to focus just on the sound of the bow during the shooting, trying to ignore everything else.

Scoring table – Sound level

Weight configuration	Very Noisy [1]	Noisy [2]	Neutral [3]	Quiet [4]	Very Quiet [5]
XXX-YYY (B)	Reference configurations				
200-250 (A)	☐	☐	☐	☐	☐
200-250 (D)	☐	☐	☐	☐	☐
200-250 (E)	☐	☐	☐	☐	☐
250-200 (A)	☐	☐	☐	☐	☐
250-200 (D)	☐	☐	☐	☐	☐
250-200 (E)	☐	☐	☐	☐	☐
350-0 (A)	☐	☐	☐	☐	☐
350-0 (C)	☐	☐	☐	☐	☐
350-0 (E)	☐	☐	☐	☐	☐
350-200 (A)	☐	☐	☐	☐	☐
350-200 (D)	☐	☐	☐	☐	☐
350-200 (E)	☐	☐	☐	☐	☐
350-250 (A)	☐	☐	☐	☐	☐
350-250 (D)	☐	☐	☐	☐	☐
350-250 (E)	☐	☐	☐	☐	☐

Sound Quality

Instructions

Please score the following weight configurations rating the sound quality associated with the shooting of the arrow. The rating goes from 1, a very high-frequency sound (high pitch), to 5 a low-frequency sound (low pitch). You are suggested to focus just on the quality of the sound of the bow during the shooting, trying to ignore everything else.

Scoring table – Sound quality

Weight configuration	Very High Pitch [1]	High Pitch [2]	Neutral Pitch [3]	Low Pitch [4]	Very Low Pitch [5]
XXX-YYY (B)	Reference configurations				
200-250 (A)	☐	☐	☐	☐	☐
200-250 (D)	☐	☐	☐	☐	☐
200-250 (E)	☐	☐	☐	☐	☐
250-200 (A)	☐	☐	☐	☐	☐
250-200 (D)	☐	☐	☐	☐	☐
250-200 (E)	☐	☐	☐	☐	☐
350-0 (A)	☐	☐	☐	☐	☐
350-0 (C)	☐	☐	☐	☐	☐
350-0 (E)	☐	☐	☐	☐	☐
350-200 (A)	☐	☐	☐	☐	☐
350-200 (D)	☐	☐	☐	☐	☐
350-200 (E)	☐	☐	☐	☐	☐
350-250 (A)	☐	☐	☐	☐	☐
350-250 (D)	☐	☐	☐	☐	☐
350-250 (E)	☐	☐	☐	☐	☐

Overall Quality of the Weight Configuration

Instructions

Please score the following weight configurations rating the quality of each configuration. The rating goes from 1, a very low quality, to 5 a very high quality. You are suggested to focus just on the sound of the bow during the shooting, trying to ignore everything else and determine the quality of the weight configuration based on the sound of the bow.

Scoring table – Quality of the Weight Configuration

Weight configuration	Very Low Quality [1]	Low Quality [2]	Neutral Quality [3]	High Quality [4]	Very High Quality [5]
XXX-YYY (B)	Reference configurations				
200-250 (A)	☐	☐	☐	☐	☐
200-250 (D)	☐	☐	☐	☐	☐
200-250 (E)	☐	☐	☐	☐	☐
250-200 (A)	☐	☐	☐	☐	☐
250-200 (D)	☐	☐	☐	☐	☐
250-200 (E)	☐	☐	☐	☐	☐
350-0 (A)	☐	☐	☐	☐	☐
350-0 (C)	☐	☐	☐	☐	☐
350-0 (E)	☐	☐	☐	☐	☐
350-200 (A)	☐	☐	☐	☐	☐
350-200 (D)	☐	☐	☐	☐	☐
350-200 (E)	☐	☐	☐	☐	☐
350-250 (A)	☐	☐	☐	☐	☐
350-250 (D)	☐	☐	☐	☐	☐
350-250 (E)	☐	☐	☐	☐	☐

Questionnaire from the Third Paper

Archer's data			Style:	Recurve	Barebow
Bow's limbs:	Name		Maker		
	Length		Man. Tech.		
Poundage [pounds]:	Nominal		On the finger		
Group:	Low poundage	Medium poundage		High poundage	

The conventional name of the tested limbs				
Motive C5 (1)	NS Foam (2)	NS Wood (3)	Sx+ (4)	Carbon Velos (5)
MXT-10 Foam (6)	MXT-10 Wood (7)	Axia ILF (8)	Axia Formula (9)	

Stiffness

Please evaluate the perceived stiffness of the tested limbs in three different phases of the drawing phase: beginning, middle and end drawing. The stiffness is a measure of the amount of force necessary to pull the string into the specified position.

At the beginning of the drawing phase:					
Limbs 1:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 2:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 3:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 4:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 5:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 6:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 7:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 8:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 9:	Very stiff	Stiff	Normal	Soft	Very soft

In the middle of the drawing phase:					
Limbs 1:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 2:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 3:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 4:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 5:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 6:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 7:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 8:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 9:	Very stiff	Stiff	Normal	Soft	Very soft

At the end of the drawing phase:					
Limbs 1:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 2:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 3:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 4:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 5:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 6:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 7:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 8:	Very stiff	Stiff	Normal	Soft	Very soft
Limbs 9:	Very stiff	Stiff	Normal	Soft	Very soft

Smoothness

Please evaluate the perceived smoothness of the tested limbs. The smoothness is related to the increment of force necessary to create an increment of draw, during the drawing phase.

Limbs 1: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Limbs 2: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Limbs 3: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Limbs 4: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Limbs 5: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Limbs 6: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Limbs 7: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Limbs 8: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Limbs 9: Do the tested limbs have the same smoothness throughout the entire draw?												Yes	No
If No, evaluate the smoothness of the different phases of the drawing:													
Beginning	+	=	-	Middle	+	=	-	End	+	=	-		

Speed of the Limbs

Please evaluate the perceived speed of the tested limbs. The speed is a measurement of how quickly the limbs react when released.

Limbs 1:				
Very quick	Quick	Normal	Slow	Very slow

Limbs 2:				
Very quick	Quick	Normal	Slow	Very slow

Limbs 3:				
Very quick	Quick	Normal	Slow	Very slow

Limbs 4:				
Very quick	Quick	Normal	Slow	Very slow

Limbs 5:				
Very quick	Quick	Normal	Slow	Very slow

Limbs 6:				
Very quick	Quick	Normal	Slow	Very slow

Limbs 7:				
Very quick	Quick	Normal	Slow	Very slow

Limbs 8:				
Very quick	Quick	Normal	Slow	Very slow

Limbs 9:				
Very quick	Quick	Normal	Slow	Very slow

Vibrations

Please evaluate the perceived vibrations of the tested limbs on release. Please try to differentiate between the mechanical vibrations (perceived through the hand) and the sound of the string (noise).

Mechanical vibrations:					
Limbs 1:	Very high	High	Normal	Low	Very low
Limbs 2:	Very high	High	Normal	Low	Very low
Limbs 3:	Very high	High	Normal	Low	Very low
Limbs 4:	Very high	High	Normal	Low	Very low
Limbs 5:	Very high	High	Normal	Low	Very low
Limbs 6:	Very high	High	Normal	Low	Very low
Limbs 7:	Very high	High	Normal	Low	Very low
Limbs 8:	Very high	High	Normal	Low	Very low
Limbs 9:	Very high	High	Normal	Low	Very low

Sound:					
Limbs 1:	Very noisy	Noisy	Normal	Quiet	Very quiet
Limbs 2:	Very noisy	Noisy	Normal	Quiet	Very quiet
Limbs 3:	Very noisy	Noisy	Normal	Quiet	Very quiet
Limbs 4:	Very noisy	Noisy	Normal	Quiet	Very quiet
Limbs 5:	Very noisy	Noisy	Normal	Quiet	Very quiet
Limbs 6:	Very noisy	Noisy	Normal	Quiet	Very quiet
Limbs 7:	Very noisy	Noisy	Normal	Quiet	Very quiet
Limbs 8:	Very noisy	Noisy	Normal	Quiet	Very quiet
Limbs 9:	Very noisy	Noisy	Normal	Quiet	Very quiet

Limbs Preference by Group

Considering the limbs in the same group, please rank the tested limbs according to your preference.

Group 1:					
Motive C5 (1)		NS Foam (2)		NS Wood (3)	

Group 2:			
Sx+ (4)		Carbon Velos (5)	

Group 3:			
MXT-10 Foam (6)		MXT-10 Wood (7)	
Axia ILF (8)		Axia Formula (9)	

Comments

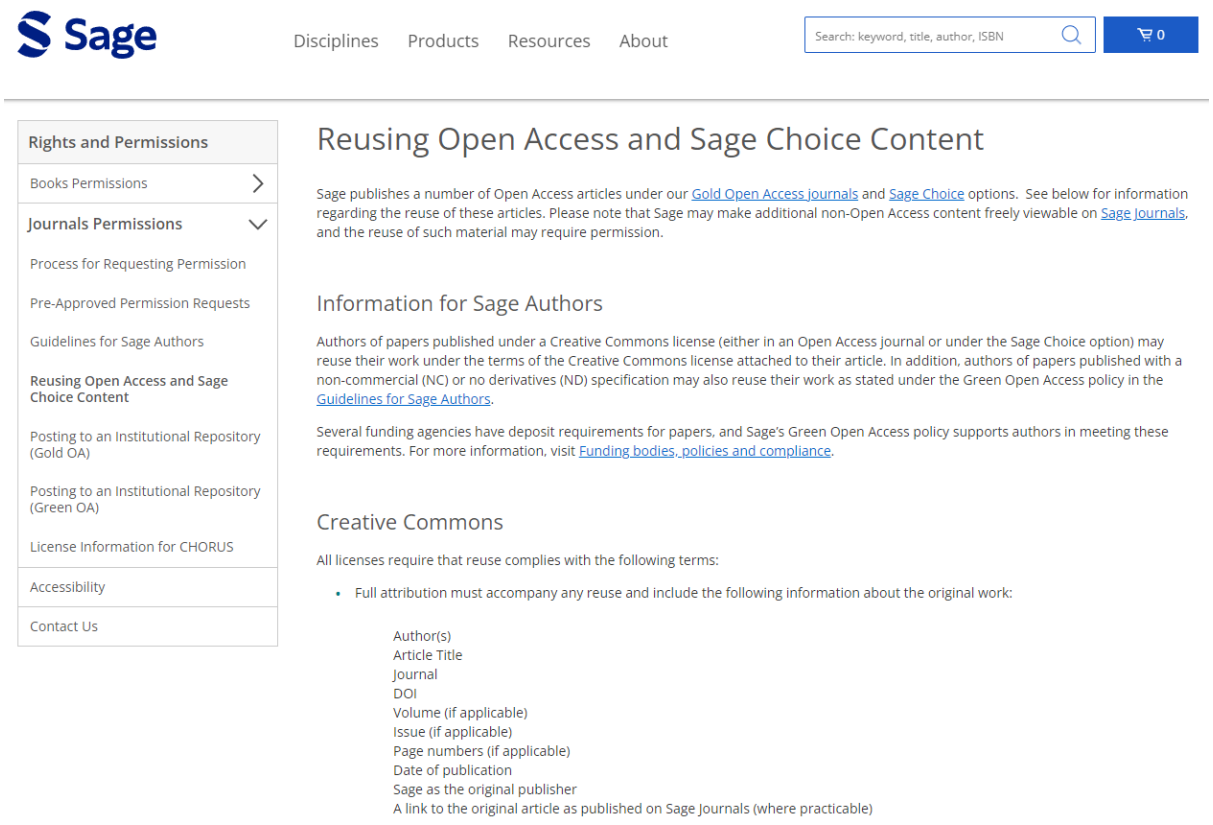
Appendix F

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The papers "*Analysis of preferred weight configuration for barebow shooting style*" and "*Objective and subjective measurements of the influence of dampers on the shooting experience of barebow archers*" are published in the "*Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*" journal, a Sage journal[16].

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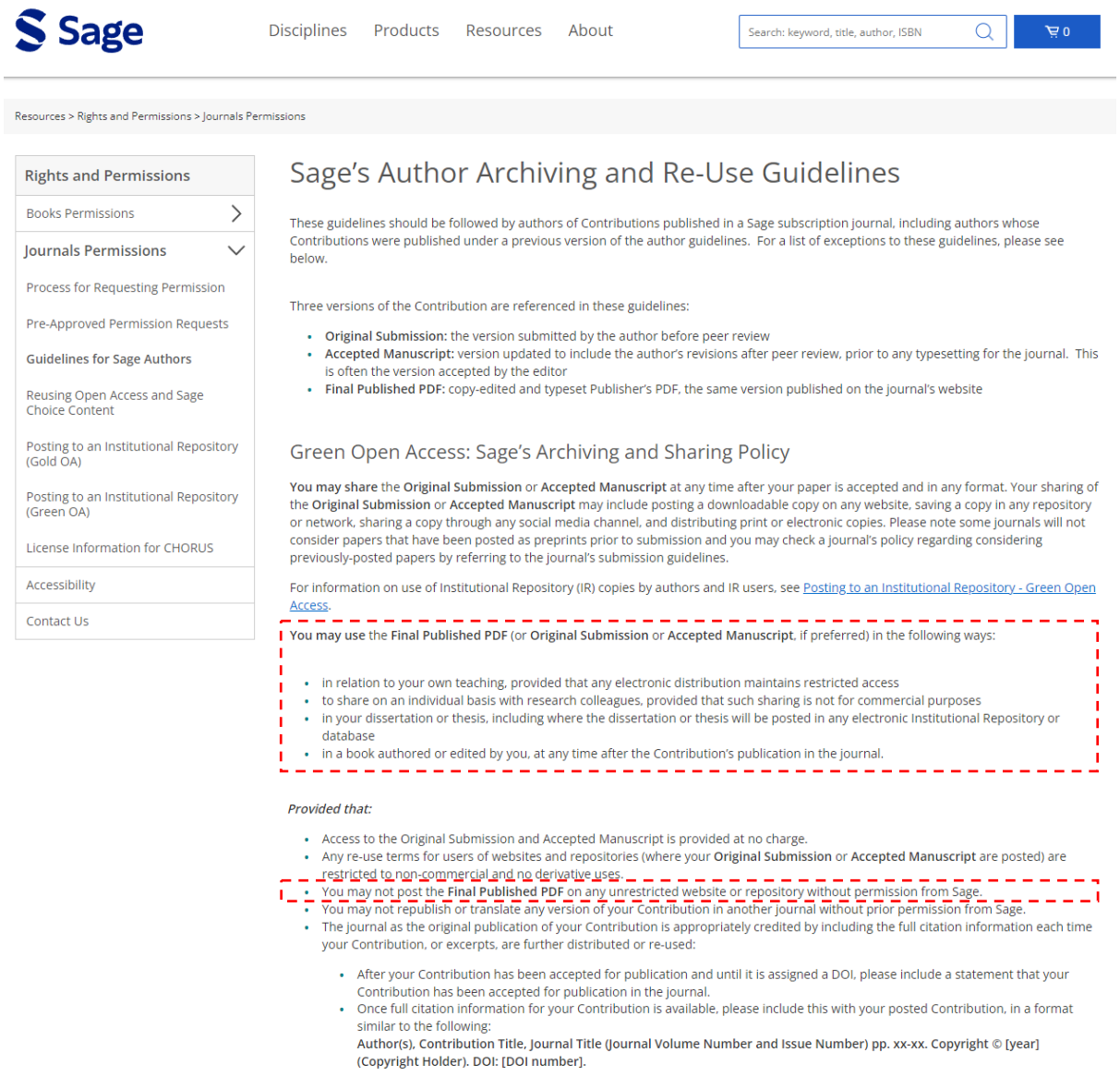
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Appendix G

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Last updated: 25 April 2023

Appendix H

Bowstring elastic compliance under loading conditions

The material used for the bowstring in the tests is BCY 8125 from the American brand BCY (https://www.bcyfibers.com/index.php), a company specialised in fibres for bowstring. BCY 8125 is a 100% SK75 Dyneema® fibre (https://www.bcyfibers.com/Bowstring.php). Chemically, Dyneema is an Ultra-high molecular weight polyethylene (UHMwPE), a thermoplastic polyethylene. This means that, while it actually falls under the umbrella of plastic, it is pliable and moldable above a certain temperature and solidifies upon cooling retaining a measure of pliability, similar to common textiles. That particular combination of factors means that, while the material is extremely flexible, it's also incredibly strong – with some claims putting it at around 15 times stronger than steel (of a similar thickness) [105] [106].

Bowstrings made of BCY 8125 are used for their resistance to wear, minimal stretch under loading conditions and minimal creep. The creep in a bowstring settles in the first few hours of use of the string, and the stretch settles in the first few shots of a session [3] [65] [9]. When considering the internal potential energy stored in the bow, the stretching of the string is ignored compared to the deformation of the limbs [31], and the bowstring is assumed to be unstretchable.

In the following experiment, the compliance of the bowstring is compared to the compliance of the bow to evaluate the correctness of the previous statement. The compliance of the bowstring and bow (or, more precisely, of the limbs) is defined as the deformation over applied load, and it is measured in mm/N.

Methodology

The tests were executed in the Archery Laboratory, North West Engineering Building, University of the Witwatersrand. The bow used in the test is representative of an Olympic-level bow, and it is comprised of the following:

- Riser Win&Win ATF-DX (25 inches, Right Handed)
- Limbs Win&Win NS-XP Wood (36 pounds nominal poundage, Long)
- String BCY 8125, 16 strands (made on the 8th of December 2024).

The bow was clamped in the testing rig (Figure 23) and connected to the winch. The initial brace height was 22.9 mm (measured from the string to the centre of the plunger). The bow was drawn for 703 mm, corresponding to a draw weight of 40 pounds (177.929 N), measured with a load cell between the winch mechanism and the string (Figure 23) (for the load cell characteristics, refer to the third paper of this thesis).

The compliance of the string was measured independently for the upper and lower segments of the bowstring, evaluating the stretch of the bowstring between two fixed points (Figure 24) using a digital vernier caliper. The compliance of the upper limb was evaluated by overlapping a picture of the limb in the brace position and a picture of the limb in the loaded position. The distance between the two pictures was evaluated using an online photo measurement service (https://eleif.net/photomeasure).



Figure 24 - Compliance test set-up.

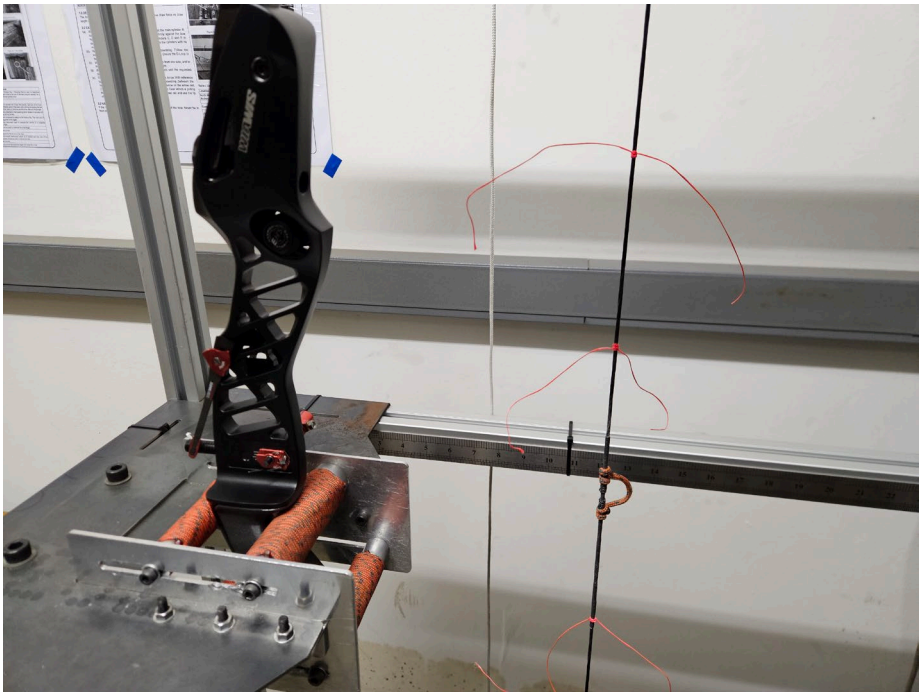


Figure 25 - Fixed points on the upper section of the bowstring.

The test was repeated three times for repeatability. In Table 3, the measurement of deformation for the upper and lower parts of the bowstring is shown. The engineering strain (indicated with *Epsilon* in Table 3) was calculated as:

$$\varepsilon = \frac{\Delta l}{l_0} = \frac{Difference}{Initial\ measure}$$

The change in length of the section of the bowstring in draw was calculated as:

$$\Delta L_{section} = \varepsilon_{average} \cdot Lenght\ of\ the\ bowstring\ section$$

Table 1 - Deformation results for the upper and lower parts of the bowstring.

Length of the bowstring

Upper section (from half of the nocking point to the tip of the limb)	785	mm
Lower section (from half of the nocking point to the tip of the limb)	780	mm

Upper half bowstring

Initial measure [mm]	Final measure [mm]	Difference [mm]	Epsilon
100.05	100.08	0.03000	0.00030
100.07	100.10	0.03000	0.00030
100.06	100.08	0.02000	0.00020
	Average:	0.02667	0.00027

Delta L upper half bowstring: 0.20921 mm

Lower half bowstring

Initial measure [mm]	Final measure [mm]	Difference [mm]	Epsilon
101.11	101.15	0.04000	0.00040
101.12	101.15	0.03000	0.00030
101.11	101.14	0.03000	0.00030
	Average:	0.0333	0.00033

Delta L half string 0.25714 mm

The elastic compliance for the string was calculated as:

$$C_{bowstring\ section} = \frac{\Delta L_{section}}{Load}$$

With the results reported in Table 4:

Table 2 - Elastic compliance of the sections of the bowstring.

Upper section of the bowstring	0.00030	[mm/N]
Lower section of the bowstring	0.00037	[mm/N]

The deformation of the tip of the upper limb was measured by overlaying an image of the limb at rest image capturing the deformed position at full draw, using a known reference distance for calibration (Figure 25). The measured deformations are reported in Table 5.

Table 3 - Elastic compliance of the upper limb.

Upper tip displacement	
129.50	mm
130.30	mm
129.70	mm
Average: 129.83	mm

Upper limb elastic compliance		
Upper limb	1.4594	[mm/N]

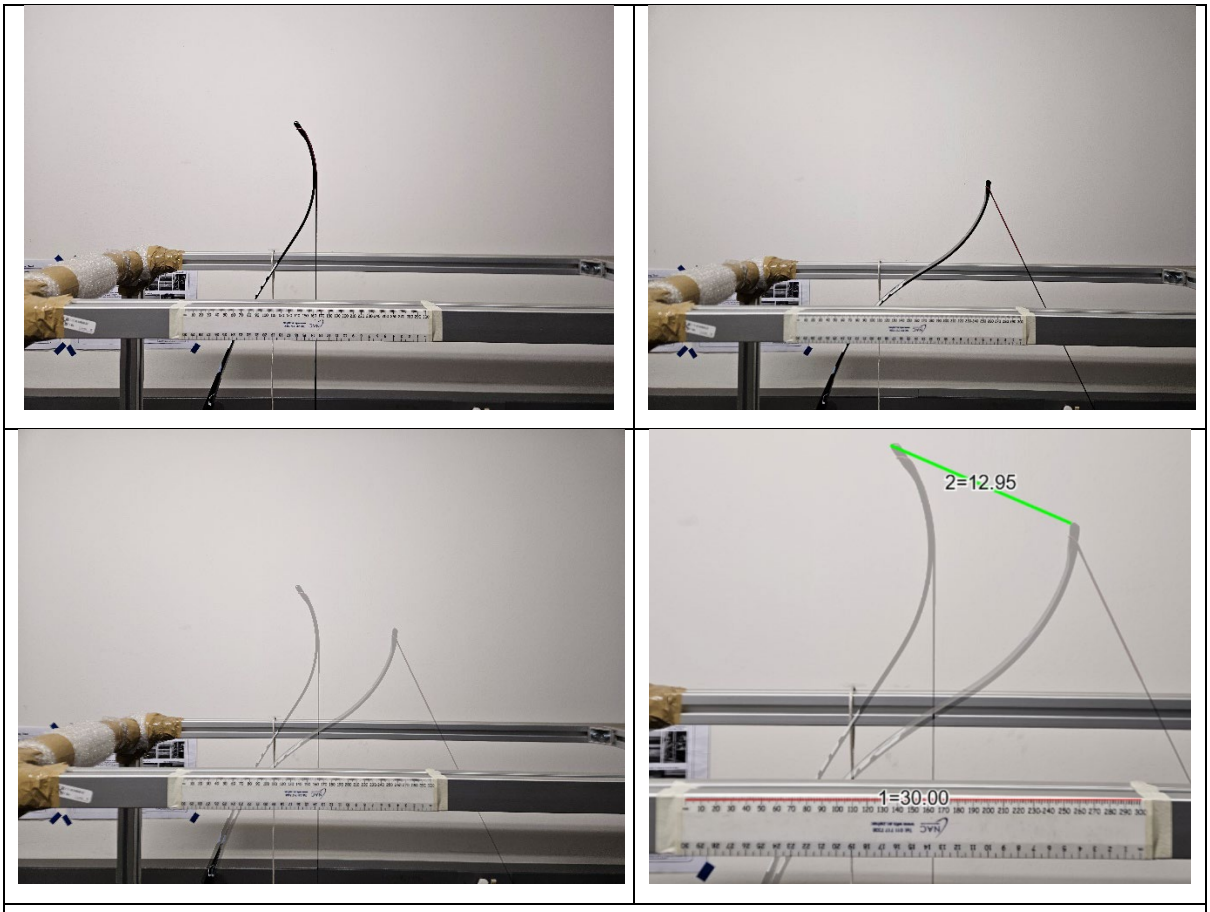


Figure 26 – First test. [Top left] The upper limb at rest. [Top right] The upper limb at full draw. [Bottom left] Overlap of the two pictures. [Bottom right] The measurement of the deformation of the tip of the upper limb.

Conclusions

The elastic compliance of the limbs is four orders of magnitude higher than the elastic compliance of the string. Compared to the deformation of the limbs, the deformation of the string is negligible, supporting the statement typical of the archery manuals that the string is practically inextensible [3] [31] [66] and it does not contribute to the storing of potential energy in the shooting cycle.

Appendix I

Matlab scripts for the first paper.

Vibration analysis – Position 1 – Configuration 200-0

Reading of the Excel spreadsheet and creation of timetables

```
clf
clear

% Time Step
Tstep = 0.000078125;

Orig = readtimetable("Pos1-200-0.xlsx","TimeStep",seconds(Tstep));
```

Plotting of the three responses on the X-axis

```
figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northwest')
```

Initial re-demensioning of the timetable

```
% Initial time
tstart = seconds(8);
% Ending time
tend = Orig.Time(end);
timeLimits = timerange(tstart,tend);
Orig = Orig(timeLimits,:);

figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
```

```
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northwest')
```

Alignment of the signals

```
Orig_1 = Orig(:,["X1","Y1","Z1"]);
Orig_2 = Orig(:,["X2","Y2","Z2"]);
Orig_3 = Orig(:,["X3","Y3","Z3"]);

X2Delay = finddelay(Orig.X1,Orig.X2);
X2Delay = seconds(X2Delay*Tstep);
Orig_2.Properties.StartTime = -X2Delay + tstart;

X3Delay = finddelay(Orig.X1,Orig.X3);
X3Delay = seconds(X3Delay*Tstep);
Orig_3.Properties.StartTime = -X3Delay + tstart;

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
plot(Orig_3.Time,Orig_3.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3")

plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3")

plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
plot(Orig_3.Time,Orig_3.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3")
```

Redemensioning of the timetable

```
% Initial time
tstart = seconds(9.7);
% Ending time
tend = tstart + seconds(1);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);

filt_amplZ = 3; % g

ii = 1;
while Orig_1.Z1(ii) <= filt_amplZ
        ii = ii + 1;
end
tstart = Orig_1.Time(ii);
tend = tstart + seconds(0.4);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
plot(Orig_3.Time,Orig_3.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3")

plot(Orig_1.Time,Orig_1.Y1)
```

```
hold on
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3")

plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
plot(Orig_3.Time,Orig_3.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3")
```

The original database is reconstructed

```
% Orig =
array2timetable([Orig_1.X1,Orig_1.Y1,Orig_1.Z1,Orig_2.X2,Orig_2.Y2,Orig_2.Z2,Orig_3.X3,Orig_3.Y3,Orig_3.Z3],"RowTimes
",Orig_1.Time);
% Orig.Properties.VariableNames = ["X1" "Y1" "Z1" "X2" "Y2" "Z2" "X3" "Y3" "Z3"];
```

Temporal Response

```
figure
stackedplot(Orig_1)
title("Temporal Response First Shot")
xlabel("Time [s]")

figure
stackedplot(Orig_2)
title("Temporal Response Second Shot")
xlabel("Time [s]")

figure
stackedplot(Orig_3)
title("Temporal Response Third Shot")
xlabel("Time [s]")
```

Time-Frequency plots: Spectrograms of the First Shot

```
max_freq = 4000;
min_freq = 0;
thres = -50;  % db

pspectrum(Orig_1.X1,Orig_1.Time,"spectrogram","FrequencyLimits",[min_freq max_freq],"MinThreshold",thres)
[p_X,f_X,t_X] = pspectrum(Orig_1.X1,Orig_1.Time,"spectrogram","FrequencyLimits",[min_freq
max_freq],"MinThreshold",thres);
pspectrum(Orig_1.Y1,Orig_1.Time,"spectrogram","FrequencyLimits",[min_freq max_freq],"MinThreshold",thres)
[p_Y,f_Y,t_Y] = pspectrum(Orig_1.Y1,Orig_1.Time,"spectrogram","FrequencyLimits",[min_freq
max_freq],"MinThreshold",thres);
pspectrum(Orig_1.Z1,Orig_1.Time,"spectrogram","FrequencyLimits",[min_freq max_freq],"MinThreshold",thres)
[p_Z,f_Z,t_Z] = pspectrum(Orig_1.Z1,Orig_1.Time,"spectrogram","FrequencyLimits",[min_freq
max_freq],"MinThreshold",thres);

% psum_X = sum(p_X);
% plot(t_X,psum_X)
% psum_Y = sum(p_Y);
% plot(t_Y,psum_Y)
% psum_Z = sum(p_Z);
% plot(t_Z,psum_Z)
```

Time-Frequency plots: Scalograms of the First Shot

```
cwt(Orig_1.X1,1/Tstep,"FrequencyLimits",[0 max_freq])
title("Magnitude Scalogram - X-direction")
%caxis([1 10])  % to change the colormap limits
cwt(Orig_1.Y1,1/Tstep,"FrequencyLimits",[0 max_freq])
title("Magnitude Scalogram - Y-direction")
%caxis([1 10])  % to change the colormap limits
cwt(Orig_1.Z1,1/Tstep,"FrequencyLimits",[0 max_freq])
title("Magnitude Scalogram - Z-direction")
%caxis([1 10])  % to change the colormap limits
```

Creation of the power spectrum of the signals of the First Shot

```
max_freq = 4000; % Hz

tiledlayout(3,1)
nexttile
pspectrum(Orig_1(:,"X1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - X Direction")
nexttile
pspectrum(Orig_1(:,"Y1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - Y Direction")
nexttile
```

```
pspectrum(Orig_1(:,"Z1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - Z Direction")

figure
[pwr_X,freq_X] = pspectrum(Orig_1(:,"X1"));
semilogx(freq_X,db(pwr_X,"power"))
title("Power Spectrum - X-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")

[pwr_Y,freq_Y] = pspectrum(Orig_1(:,"Y1"));
semilogx(freq_Y,db(pwr_Y,"power"))
title("Power Spectrum - Y-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")

[pwr_Z,freq_Z] = pspectrum(Orig_1(:,"Z1"));
semilogx(freq_Z,db(pwr_Z,"power"))
title("Power Spectrum - Z-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
```

Signal Statisics in Local Coordinate System

```
% Max_X1 = max(Orig.X1);
% Min_X1 = min(Orig.X1);
% Mean_X1 = mean(Orig.X1);
% MeanS_X1 = mean(Orig.X1 .^ 2);
% E_X1 = sum(Orig.X1 .^ 2);

P2P_X1 = peak2peak(Orig_1.X1);
P2P_X2 = peak2peak(Orig_2.X2);
P2P_X3 = peak2peak(Orig_3.X3);
P2P_X = (P2P_X1 + P2P_X2 + P2P_X3)/3;
P2P_Y1 = peak2peak(Orig_1.Y1);
P2P_Y2 = peak2peak(Orig_2.Y2);
P2P_Y3 = peak2peak(Orig_3.Y3);
P2P_Y = (P2P_Y1 + P2P_Y2 + P2P_Y3)/3;
P2P_Z1 = peak2peak(Orig_1.Z1);
P2P_Z2 = peak2peak(Orig_2.Z2);
P2P_Z3 = peak2peak(Orig_3.Z3);
P2P_Z = (P2P_Z1 + P2P_Z2 + P2P_Z3)/3;

RMS_X1 = rms(Orig_1.X1);
RMS_X2 = rms(Orig_2.X2);
RMS_X3 = rms(Orig_3.X3);
RMS_X = (RMS_X1 + RMS_X2 + RMS_X3)/3;
RMS_Y1 = rms(Orig_1.Y1);
RMS_Y2 = rms(Orig_2.Y2);
RMS_Y3 = rms(Orig_3.Y3);
RMS_Y = (RMS_Y1 + RMS_Y2 + RMS_Y3)/3;
RMS_Z1 = rms(Orig_1.Z1);
RMS_Z2 = rms(Orig_2.Z2);
RMS_Z3 = rms(Orig_3.Z3);
RMS_Z = (RMS_Z1 + RMS_Z2 + RMS_Z3)/3;
```

Print the output

```
vp.a = [P2P_X1 P2P_X2 P2P_X3; P2P_Y1 P2P_Y2 P2P_Y3; P2P_Z1 P2P_Z2 P2P_Z3];
vp.b = [RMS_X1 RMS_X2 RMS_X3; RMS_Y1 RMS_Y2 RMS_Y3; RMS_Z1 RMS_Z2 RMS_Z3];

save('Pos1-200-0-L.txt','-struct','vp','-ascii')
```

Signal Statistics in Global Coordinate System

```
% local X --> global Y with a counterclockwise angle of 24 deg.
% local Y --> global Z
% local Z --> global X with a counterclockwise angle of 24 deg.

Ang = 24 * pi / 180; % angle in radians

P2P_X1_G = cos(Ang) * P2P_Z1 - sin(Ang) * P2P_X1;
P2P_X2_G = cos(Ang) * P2P_Z2 - sin(Ang) * P2P_X2;
P2P_X3_G = cos(Ang) * P2P_Z3 - sin(Ang) * P2P_X3;

P2P_Y1_G = sin(Ang) * P2P_Z1 + cos(Ang) * P2P_X1;
P2P_Y2_G = sin(Ang) * P2P_Z2 + cos(Ang) * P2P_X2;
P2P_Y3_G = sin(Ang) * P2P_Z3 + cos(Ang) * P2P_X3;

P2P_Z1_G = P2P_Y1;
P2P_Z2_G = P2P_Y2;
P2P_Z3_G = P2P_Y3;

RMS_X1_G = cos(Ang) * RMS_Z1 - sin(Ang) * RMS_X1;
RMS_X2_G = cos(Ang) * RMS_Z2 - sin(Ang) * RMS_X2;
RMS_X3_G = cos(Ang) * RMS_Z3 - sin(Ang) * RMS_X3;

RMS_Y1_G = sin(Ang) * RMS_Z1 + cos(Ang) * RMS_X1;
RMS_Y2_G = sin(Ang) * RMS_Z2 + cos(Ang) * RMS_X2;
```

```
RMS_Y3_G = sin(Ang) * RMS_Z3 + cos(Ang) * RMS_X3;

RMS_Z1_G = RMS_Y1;
RMS_Z2_G = RMS_Y2;
RMS_Z3_G = RMS_Y3;
```

Print the output

```
vp.a = [P2P_X1_G P2P_X2_G P2P_X3_G;P2P_Y1_G P2P_Y2_G P2P_Y3_G;P2P_Z1_G P2P_Z2_G P2P_Z3_G];
vp.b = [RMS_X1_G RMS_X2_G RMS_X3_G;RMS_Y1_G RMS_Y2_G RMS_Y3_G;RMS_Z1_G RMS_Z2_G RMS_Z3_G];

save('Pos1-200-0-G.txt','-struct','vp','-ascii')
```

Lowpass Filter for the First Shot

```
filt_freq = 3000;  % HZ

figure
lowpass(Orig_1(:,"X1"),filt_freq)
figure
lowpass(Orig_1(:,"Y1"),filt_freq)
figure
lowpass(Orig_1(:,"Z1"),filt_freq)

Orig_1_filt = lowpass(Orig_1,filt_freq);
```

Creation of the power spectrum of the filtered signals for the First Shot

```
tiledlayout(3,1)
nexttile
pspectrum(Orig_1_filt(:,"X1"),"FrequencyLimits",[0 3000])
title("Power Spectrum - X Direction")
nexttile
pspectrum(Orig_1_filt(:,"Y1"),"FrequencyLimits",[0 3000])
title("Power Spectrum - Y Direction")
nexttile
pspectrum(Orig_1_filt(:,"Z1"),"FrequencyLimits",[0 3000])
title("Power Spectrum - Z Direction")

figure
[pwr_X,freq_X] = pspectrum(Orig_1_filt(:,"X1"),"FrequencyLimits",[0 3000]);
semilogx(freq_X,db(pwr_X,"power"))
title("Power Spectrum - X-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")

[pwr_Y,freq_Y] = pspectrum(Orig_1_filt(:,"Y1"),"FrequencyLimits",[0 3000]);
semilogx(freq_Y,db(pwr_Y,"power"))
title("Power Spectrum - Y-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")

[pwr_Z,freq_Z] = pspectrum(Orig_1_filt(:,"Z1"),"FrequencyLimits",[0 3000]);
semilogx(freq_Z,db(pwr_Z,"power"))
title("Power Spectrum - Z-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
```

Vibration analysis – Position 1 – Configuration 200-0 – Filtered data

Reading of the Excel spreadsheet and creation of timetables

```
clf
clear

% Time Step
Tstep = 0.000078125;

Orig = readtimetable("Pos1-200-0.xlsx","TimeStep",seconds(Tstep));
```

Plotting of the three responses on the X-axis

```
figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
```

```
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northwest')
```

Initial redemensioning of the timetable

```
% Initial time
tstart = seconds(8);
% Ending time
tend = Orig.Time(end);
timeLimits = timerange(tstart,tend);
Orig = Orig(timeLimits,:);

figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northwest')
```

Alignment of the signals

```
Orig_1 = Orig(:,["X1","Y1","Z1"]);
Orig_2 = Orig(:,["X2","Y2","Z2"]);
Orig_3 = Orig(:,["X3","Y3","Z3"]);

X2Delay = finddelay(Orig.X1,Orig.X2);
X2Delay = seconds(X2Delay*Tstep);
Orig_2.Properties.StartTime = -X2Delay + tstart;

X3Delay = finddelay(Orig.X1,Orig.X3);
X3Delay = seconds(X3Delay*Tstep);
Orig_3.Properties.StartTime = -X3Delay + tstart;

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
plot(Orig_3.Time,Orig_3.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3")

plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3")
```

```
plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
plot(Orig_3.Time,Orig_3.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3")
```

Redemensioning of the timetable

```
% Initial time
tstart = seconds(9.7);
% Ending time
tend = tstart + seconds(1);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);

filt_amplZ = 3; % g

ii = 1;
while Orig_1.Z1(ii) <= filt_amplZ
        ii = ii + 1;
end
tstart = Orig_1.Time(ii);
tend = tstart + seconds(0.4);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
plot(Orig_3.Time,Orig_3.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3")

plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3")

plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
plot(Orig_3.Time,Orig_3.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3")
```

Lowpass Filter for the Shots

```
filt_freq = 500;  % HZ

figure
lowpass(Orig_1(:,"X1"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_1(:,"Y1"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_1(:,"Z1"),filt_freq,'Steepness',0.99)

Orig_1_f = lowpass(Orig_1,filt_freq,'Steepness',0.99);

figure
lowpass(Orig_2(:,"X2"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_2(:,"Y2"),filt_freq,'Steepness',0.99)
figure
```

```
lowpass(Orig_2(:,"Z2"),filt_freq,'Steepness',0.99)

Orig_2_f = lowpass(Orig_2,filt_freq,'Steepness',0.99);

figure
lowpass(Orig_3(:,"X3"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_3(:,"Y3"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_3(:,"Z3"),filt_freq,'Steepness',0.99)

Orig_3_f = lowpass(Orig_3,filt_freq,'Steepness',0.99);

figure
stackedplot(Orig_1_f)
title("Temporal Response First Shot - Filtered")
xlabel("Time [s]")

figure
stackedplot(Orig_2_f)
title("Temporal Response Second Shot - Filtered")
xlabel("Time [s]")

figure
stackedplot(Orig_3_f)
title("Temporal Response Third Shot - Filtered")
xlabel("Time [s]")
```

Rainflow counting method for the filtered signal

```
[c_X1,rm_X1,rmr_X1,rmm_X1] = rainflow(Orig_1_f(:,"X1"));
[c_X2,rm_X2,rmr_X2,rmm_X2] = rainflow(Orig_2_f(:,"X2"));
[c_X3,rm_X3,rmr_X3,rmm_X3] = rainflow(Orig_3_f(:,"X3"));

[c_Y1,rm_Y1,rmr_Y1,rmm_Y1] = rainflow(Orig_1_f(:,"Y1"));
[c_Y2,rm_Y2,rmr_Y2,rmm_Y2] = rainflow(Orig_2_f(:,"Y2"));
[c_Y3,rm_Y3,rmr_Y3,rmm_Y3] = rainflow(Orig_3_f(:,"Y3"));

[c_Z1,rm_Z1,rmr_Z1,rmm_Z1] = rainflow(Orig_1_f(:,"Z1"));
[c_Z2,rm_Z2,rmr_Z2,rmm_Z2] = rainflow(Orig_2_f(:,"Z2"));
[c_Z3,rm_Z3,rmr_Z3,rmm_Z3] = rainflow(Orig_3_f(:,"Z3"));

histogram('BinEdges',rmr_X1','BinCounts',sum(rm_X1,2))
hold on
histogram('BinEdges',rmr_Y1','BinCounts',sum(rm_Y1,2))
histogram('BinEdges',rmr_Z1','BinCounts',sum(rm_Z1,2))
hold off
title('First Shot (Filtered)')
xlabel('Stress Range')
ylabel('Cycle Counts')
legend('X1','Y1','Z1')

histogram('BinEdges',rmr_X2','BinCounts',sum(rm_X2,2))
hold on
histogram('BinEdges',rmr_Y2','BinCounts',sum(rm_Y2,2))
histogram('BinEdges',rmr_Z2','BinCounts',sum(rm_Z2,2))
hold off
title('Second Shot (Filtered)')
xlabel('Stress Range')
ylabel('Cycle Counts')
legend('X2','Y2','Z2')

histogram('BinEdges',rmr_X3','BinCounts',sum(rm_X3,2))
hold on
histogram('BinEdges',rmr_Y3','BinCounts',sum(rm_Y3,2))
histogram('BinEdges',rmr_Z3','BinCounts',sum(rm_Z3,2))
hold off
title('Third Shot (Filtered)')
xlabel('Stress Range')
ylabel('Cycle Counts')
legend('X3','Y3','Z3')
```

Equivalent damage for Rainflow calculations

```
Sz = size(rmr_X1,1);
Sm = sum(rm_X1,2);
Cc = rmr_X1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_X1 = sum(Dg);

Sz = size(rmr_X2,1);
Sm = sum(rm_X2,2);
Cc = rmr_X2;
```

```
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_X2 = sum(Dg);

Sz = size(rmr_X3,1);
Sm = sum(rm_X3,2);
Cc = rmr_X3;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_X3 = sum(Dg);

Sz = size(rmr_Y1,1);
Sm = sum(rm_Y1,2);
Cc = rmr_Y1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Y1 = sum(Dg);

Sz = size(rmr_Y2,1);
Sm = sum(rm_Y2,2);
Cc = rmr_Y2;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Y2 = sum(Dg);

Sz = size(rmr_Y3,1);
Sm = sum(rm_Y3,2);
Cc = rmr_Y3;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Y3 = sum(Dg);

Sz = size(rmr_Z1,1);
Sm = sum(rm_Z1,2);
Cc = rmr_Z1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Z1 = sum(Dg);

Sz = size(rmr_Z2,1);
Sm = sum(rm_Z2,2);
Cc = rmr_Z2;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Z2 = sum(Dg);

Sz = size(rmr_Z3,1);
Sm = sum(rm_Z3,2);
Cc = rmr_Z3;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Z3 = sum(Dg);
```

Signal Statistics in Local Coordinate System

```
P2P_X1 = peak2peak(Orig_1_f.X1);
P2P_X2 = peak2peak(Orig_2_f.X2);
P2P_X3 = peak2peak(Orig_3_f.X3);

P2P_Y1 = peak2peak(Orig_1_f.Y1);
P2P_Y2 = peak2peak(Orig_2_f.Y2);
P2P_Y3 = peak2peak(Orig_3_f.Y3);
```

```
P2P_Z1 = peak2peak(Orig_1_f.Z1);
P2P_Z2 = peak2peak(Orig_2_f.Z2);
P2P_Z3 = peak2peak(Orig_3_f.Z3);

RMS_X1 = rms(Orig_1_f.X1);
RMS_X2 = rms(Orig_2_f.X2);
RMS_X3 = rms(Orig_3_f.X3);

RMS_Y1 = rms(Orig_1_f.Y1);
RMS_Y2 = rms(Orig_2_f.Y2);
RMS_Y3 = rms(Orig_3_f.Y3);

RMS_Z1 = rms(Orig_1_f.Z1);
RMS_Z2 = rms(Orig_2_f.Z2);
RMS_Z3 = rms(Orig_3_f.Z3);
```

Signal Statistics in Global Coordinate System

```
% local X --> global Y with a counterclockwise angle of 24 deg.
% local Y --> global Z
% local Z --> global X with a counterclockwise angle of 24 deg.

Ang = 24 * pi / 180; % angle in radians

P2P_X1_G = cos(Ang) * P2P_Z1 - sin(Ang) * P2P_X1;
P2P_X2_G = cos(Ang) * P2P_Z2 - sin(Ang) * P2P_X2;
P2P_X3_G = cos(Ang) * P2P_Z3 - sin(Ang) * P2P_X3;

P2P_Y1_G = sin(Ang) * P2P_Z1 + cos(Ang) * P2P_X1;
P2P_Y2_G = sin(Ang) * P2P_Z2 + cos(Ang) * P2P_X2;
P2P_Y3_G = sin(Ang) * P2P_Z3 + cos(Ang) * P2P_X3;

P2P_Z1_G = P2P_Y1;
P2P_Z2_G = P2P_Y2;
P2P_Z3_G = P2P_Y3;

RMS_X1_G = cos(Ang) * RMS_Z1 - sin(Ang) * RMS_X1;
RMS_X2_G = cos(Ang) * RMS_Z2 - sin(Ang) * RMS_X2;
RMS_X3_G = cos(Ang) * RMS_Z3 - sin(Ang) * RMS_X3;

RMS_Y1_G = sin(Ang) * RMS_Z1 + cos(Ang) * RMS_X1;
RMS_Y2_G = sin(Ang) * RMS_Z2 + cos(Ang) * RMS_X2;
RMS_Y3_G = sin(Ang) * RMS_Z3 + cos(Ang) * RMS_X3;

RMS_Z1_G = RMS_Y1;
RMS_Z2_G = RMS_Y2;
RMS_Z3_G = RMS_Y3;

Damage_X1_G = cos(Ang) * Damage_Z1 - sin(Ang) * Damage_X1;
Damage_X2_G = cos(Ang) * Damage_Z2 - sin(Ang) * Damage_X2;
Damage_X3_G = cos(Ang) * Damage_Z3 - sin(Ang) * Damage_X3;

Damage_Y1_G = sin(Ang) * Damage_Z1 + cos(Ang) * Damage_X1;
Damage_Y2_G = sin(Ang) * Damage_Z2 + cos(Ang) * Damage_X2;
Damage_Y3_G = sin(Ang) * Damage_Z3 + cos(Ang) * Damage_X3;

Damage_Z1_G = Damage_Y1;
Damage_Z2_G = Damage_Y2;
Damage_Z3_G = Damage_Y3;
```

Print the output

```
vp.a = [P2P_X1_G P2P_X2_G P2P_X3_G;P2P_Y1_G P2P_Y2_G P2P_Y3_G;P2P_Z1_G P2P_Z2_G P2P_Z3_G];
vp.b = [RMS_X1_G RMS_X2_G RMS_X3_G;RMS_Y1_G RMS_Y2_G RMS_Y3_G;RMS_Z1_G RMS_Z2_G RMS_Z3_G];
vp.c = [Damage_X1_G Damage_X2_G Damage_X3_G;Damage_Y1_G Damage_Y2_G Damage_Y3_G;Damage_Z1_G Damage_Z2_G Damage_Z3_G];

save(['Pos1-200-0-G.txt'],'-struct','vp','-ascii')
```

Vibration analysis – Shooting simulator

Program to calculate the score distribution of a set of arrows.
The calculations are based on Park paper: Using group sizes to optimise archery equipment.

```
clf
clc
clear

% Define the number of ends shot (6 arrows per end)
ends_n = 50;

n_arrows = ends_n * 6;

% Archer Skill Index (66.8)
asi = 120;
% Target distance [m]
D = 70;
```

```
W = exp(-0.027*asi+2.57)*(0.815*D+0.185*D*D/50);

% Montecarlo group width mean
Mwm1 = 2.53*W;
% Montecarlo group standard deviation
Msd1 = 0.33*W;
```

Average score with 3 standard deviations (confidence 99%)

```
% Number of trials
num_1 = 5000;
score1 = zeros(num_1,1);

for i = 1:num_1
    dist_1sd = Mwm1 + 3*2*Msd1;

    dist_1 = (-dist_1sd/2) + (dist_1sd/2 + dist_1sd/2) .* rand(n_arrows,1);
    ang_1 = zeros(n_arrows,1);

    for k = 1:n_arrows
        if dist_1(k) < 0
            ang_1(k) = (90 + (90 - 270) .* rand(1))*pi/180;
        else
            ang_1(k) = (-90 + (90 + 90) .* rand(1))*pi/180;
        end
    end

    [dist_sx, dist_sy] = pol2cart(ang_1, dist_1);

    ang = linspace(0, 2*pi);
    xp = cos(ang);
    yp = sin(ang);

    if i == 1
        scatter(dist_sx, dist_sy)
        hold on
        plot(61*xp, 61*yp, 'k');
        plot(122*xp, 122*yp, 'k');
        plot(183*xp, 183*yp, 'k');
        plot(244*xp, 244*yp, 'k');
        plot(305*xp, 305*yp, 'k');
        plot(366*xp, 366*yp, 'k');
        plot(427*xp, 427*yp, 'k');
        plot(488*xp, 488*yp, 'k');
        plot(549*xp, 549*yp, 'k');
        plot(610*xp, 610*yp, 'k');
        hold off
        title('Arrow distribution for the first trial')
        xlabel('Distance [mm]')
        ylabel('Distance [mm]')
        xlim([-650 650])
        ylim([-650 650])
    end

    score = zeros(n_arrows,1);

    for j = 1:n_arrows
        if abs(dist_1(j)) <= (61+5)
            score(j) = 10;
        elseif abs(dist_1(j)) <= (122+5) && abs(dist_1(j)) > (61+5)
            score(j) = 9;
        elseif abs(dist_1(j)) <= (183+5) && abs(dist_1(j)) > (122+5)
            score(j) = 8;
        elseif abs(dist_1(j)) <= (244+5) && abs(dist_1(j)) > (183+5)
            score(j) = 7;
        elseif abs(dist_1(j)) <= (305+5) && abs(dist_1(j)) > (244+5)
            score(j) = 6;
        elseif abs(dist_1(j)) <= (366+5) && abs(dist_1(j)) > (305+5)
            score(j) = 5;
        elseif abs(dist_1(j)) <= (427+5) && abs(dist_1(j)) > (366+5)
            score(j) = 4;
        elseif abs(dist_1(j)) <= (488+5) && abs(dist_1(j)) > (427+5)
            score(j) = 3;
        elseif abs(dist_1(j)) <= (549+5) && abs(dist_1(j)) > (488+5)
            score(j) = 2;
        elseif abs(dist_1(j)) <= (610+5) && abs(dist_1(j)) > (549+5)
            score(j) = 1;
        end
    end

    score1(i) = sum(score);
end

min_score = min(score1)
avg_score = mean(score1)
```

```
max_score = max(score1)

sd_1 = zeros(num_1,1);
for z = 1:num_1
    sd_1(z) = (score1(z) - avg_score)^2;
end
sd = sqrt(sum(sd_1)/num_1)
[sd1_score] = [avg_score - sd, avg_score + sd]
[sd2_score] = [avg_score - 2*sd, avg_score + 2*sd]
```

Matlab scripts for the second paper.

Vibration analysis – Position 1 – Configuration 200-0-A

Reading of the Excel spreadsheet and creation of timetables

```
clf
clear

% Time Step
Tstep = 0.000078125;

Orig = readtimetable("Pos1-200-0-A.xlsx","TimeStep",seconds(Tstep));
```

Plotting of the three responses on the X-axis

```
figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northwest')
```

Initial redemensioning of the timetable

```
% Initial time
tstart = seconds(8);
% Ending time
tend = Orig.Time(end);
timeLimits = timerange(tstart,tend);
Orig = Orig(timeLimits,:);

figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
```

```
legend("Z1","Z2","Z3",'location','northwest')
```

Alignment of the signals
Choose **two** signals if there are three

```
Orig_1 = Orig(:,["X1","Y1","Z1"]);
Orig_2 = Orig(:,["X2","Y2","Z2"]);

X2Delay = finddelay(Orig.X1,Orig.X2);
X2Delay = seconds(X2Delay*Tstep);
Orig_2.Properties.StartTime = -X2Delay + tstart;

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2")

plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2")

plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2")
```

Redemensioning of the timetable

```
% Initial time
tstart = seconds(10.5);
% Ending time
tend = tstart + seconds(1);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);

filt_amplZ = 3; % g

ii = 1;
while Orig_1.Z1(ii) <= filt_amplZ
        ii = ii + 1;
end
tstart = Orig_1.Time(ii);
tend = tstart + seconds(0.4);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2")

plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2")

plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
hold off
```

```
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2")
```

Temporal Response

```
figure
stackedplot(Orig_1)
title("Temporal Response First Shot")
xlabel("Time [s]")

figure
stackedplot(Orig_2)
title("Temporal Response Second Shot")
xlabel("Time [s]")
```

Creation of the power spectrum of the signals of the First Shot

```
max_freq = 4000; % Hz

tiledlayout(3,1)
nexttile
pspectrum(Orig_1(:,"X1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - X Direction")
nexttile
pspectrum(Orig_1(:,"Y1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - Y Direction")
nexttile
pspectrum(Orig_1(:,"Z1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - Z Direction")

figure
[pwr_X,freq_X] = pspectrum(Orig_1(:,"X1"));
semilogx(freq_X,db(pwr_X,"power"))
title("Power Spectrum - X-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")

[pwr_Y,freq_Y] = pspectrum(Orig_1(:,"Y1"));
semilogx(freq_Y,db(pwr_Y,"power"))
title("Power Spectrum - Y-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")

[pwr_Z,freq_Z] = pspectrum(Orig_1(:,"Z1"));
semilogx(freq_Z,db(pwr_Z,"power"))
title("Power Spectrum - Z-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
```

Signal Statistics in Local Coordinate System

```
P2P_X1 = peak2peak(Orig_1.X1);
P2P_X2 = peak2peak(Orig_2.X2);

P2P_Y1 = peak2peak(Orig_1.Y1);
P2P_Y2 = peak2peak(Orig_2.Y2);

P2P_Z1 = peak2peak(Orig_1.Z1);
P2P_Z2 = peak2peak(Orig_2.Z2);

RMS_X1 = rms(Orig_1.X1);
RMS_X2 = rms(Orig_2.X2);

RMS_Y1 = rms(Orig_1.Y1);
RMS_Y2 = rms(Orig_2.Y2);

RMS_Z1 = rms(Orig_1.Z1);
RMS_Z2 = rms(Orig_2.Z2);
```

Signal Statistics in Global Coordinate System

```
% local X --> global Y with a counterclockwise angle of 24 deg.
% local Y --> global Z
% local Z --> global X with a counterclockwise angle of 24 deg.

Ang = 24 * pi / 180; % angle in radians

P2P_X1_G = cos(Ang) * P2P_Z1 - sin(Ang) * P2P_X1;
P2P_X2_G = cos(Ang) * P2P_Z2 - sin(Ang) * P2P_X2;

P2P_Y1_G = sin(Ang) * P2P_Z1 + cos(Ang) * P2P_X1;
P2P_Y2_G = sin(Ang) * P2P_Z2 + cos(Ang) * P2P_X2;

P2P_Z1_G = P2P_Y1;
P2P_Z2_G = P2P_Y2;

RMS_X1_G = cos(Ang) * RMS_Z1 - sin(Ang) * RMS_X1;
```

```
RMS_X2_G = cos(Ang) * RMS_Z2 - sin(Ang) * RMS_X2;

RMS_Y1_G = sin(Ang) * RMS_Z1 + cos(Ang) * RMS_X1;
RMS_Y2_G = sin(Ang) * RMS_Z2 + cos(Ang) * RMS_X2;

RMS_Z1_G = RMS_Y1;
RMS_Z2_G = RMS_Y2;
```

Print the output

```
vp.a = [P2P_X1_G P2P_X2_G;P2P_Y1_G P2P_Y2_G;P2P_Z1_G P2P_Z2_G];
vp.b = [RMS_X1_G RMS_X2_G;RMS_Y1_G RMS_Y2_G;RMS_Z1_G RMS_Z2_G];

save('Pos1-200-0-E.txt','-struct','vp','-ascii')
```

Duration analysis – Position 1

Reading of the Excel spreadsheet and creation of time tables

```
clf
clear

% Time Step
Tstep = 0.000078125;

for jj = 1:5

    if jj == 1
        Orig = readtimetable("Pos1-200-0-A.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(7.5);
    elseif jj == 2
        Orig = readtimetable("Pos1-200-0-B.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(11.1);
    elseif jj == 3
        Orig = readtimetable("Pos1-200-0-C.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(10.5);
    elseif jj == 4
        Orig = readtimetable("Pos1-200-0-D.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(8.5);
    elseif jj == 5
        Orig = readtimetable("Pos1-200-0-E.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(10.5);
    end
```

The timetable is reduced according to the defined cutting time

```
    Orig_1 = Orig(:,["X1","Y1","Z1"]);
    Orig_2 = Orig(:,["X2","Y2","Z2"]);

    Z2Delay = finddelay(Orig.Z1,Orig.Z2);
    Z2Delay = seconds(Z2Delay*Tstep);
    Orig_2.Properties.StartTime = -Z2Delay;

    plot(Orig_1.Time,Orig_1.Z1)
    hold on
    plot(Orig_2.Time,Orig_2.Z2)
    hold off
    title("Acceleration Z-axis")
    xlabel("Time [s]")
    ylabel("Acceleration [g]")
    legend("Z1","Z2",'location','northwest')
```

```
    % End time
    end_time_1 = Orig_1.Time(end);
    end_time_2 = Orig_2.Time(end);

    if end_time_1 >= end_time_2
        end_time = end_time_2;
    else
        end_time = end_time_1;
    end

    timeLimits = timerange(start_time,end_time);

    Orig_1 = Orig_1(timeLimits,:);
    Orig_2 = Orig_2(timeLimits,:);
```

Filtering of the data

```
    P2P_Z1 = peak2peak(Orig_1.Z1);
    P2P_Z2 = peak2peak(Orig_2.Z2);

    if P2P_Z1 >= P2P_Z2
        P2P_Z = P2P_Z1;
    else
        P2P_Z = P2P_Z2;
    end
```

```
    filt_ampl = P2P_Z * 0.05;  % 5% of the original amplitude of the signal [g]
    Size_Orig_1 = size(Orig_1,1);

    for ii = 1:Size_Orig_1
        if Orig_1.Z1(ii) <= filt_ampl
            Orig_1.Z1(ii) = 0;
        end
        if Orig_2.Z2(ii) <= filt_ampl
            Orig_2.Z2(ii) = 0;
        end
    end

    plot(Orig_1.Time,Orig_1.Z1)
    hold on
    plot(Orig_2.Time,Orig_2.Z2)
    hold off
    title("Acceleration Z-axis")
    xlabel("Time [s]")
    ylabel("Acceleration [g]")
    legend("Z1","Z2",'location','northeast')
```

Research of the starting time and end time of the event

```
    ii = 1;
    while Orig_1.Z1(ii) == 0
        ii = ii + 1;
    end
    Z11 = Orig_1.Time(ii);
    ii = Size_Orig_1;
    while Orig_1.Z1(ii) == 0
        ii = ii - 1;
    end
    Z12 = Orig_1.Time(ii);
    DZ1 = seconds(Z12 - Z11);

    ii = 1;
    while Orig_2.Z2(ii) == 0
        ii = ii + 1;
    end
    Z21 = Orig_2.Time(ii);
    ii = Size_Orig_1;
    while Orig_2.Z2(ii) == 0
        ii = ii - 1;
    end
    Z22 = Orig_2.Time(ii);
    DZ2 = seconds(Z22 - Z21);
```

Saving of the results

```
    Res = [DZ1; DZ2];

    if jj == 1
        save('Dur_200-0.txt','Res','-ascii')
    else
        save('Dur_200-0.txt','Res','-ascii','-append')
    end

end
```

Vibration analysis – Position 1 – Configuration 200-0-A – Filtered data

Reading of the Excel spreadsheet and creation of timetables

```
clf
clear

% Time Step
Tstep = 0.000078125;

Orig = readtimetable("Pos1-200-0-A.xlsx","TimeStep",seconds(Tstep));
```

Plotting of the three responses on the X-axis

```
figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
```

```
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northwest')
```

Initial redemensioning of the timetable

```
% Initial time
tstart = seconds(6);
% Ending time
tend = Orig.Time(end);
timeLimits = timerange(tstart,tend);
Orig = Orig(timeLimits,:);

figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northwest')
```

Alignment of the signals
Choose **two** signals if there are three

```
Orig_1 = Orig(:,["X1","Y1","Z1"]);
Orig_2 = Orig(:,["X2","Y2","Z2"]);

%Orig_2 = renamevars(Orig_2,["X3","Y3","Z3"],["X2","Y2","Z2"]);

X2Delay = finddelay(Orig.X1,Orig.X2);
X2Delay = seconds(X2Delay*Tstep);
Orig_2.Properties.StartTime = -X2Delay + tstart;

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2")

plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2")

plot(Orig_1.Time,Orig_1.Z1)
```

```
hold on
plot(Orig_2.Time,Orig_2.Z2)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2")
```

Redemensioning of the timetable

```
% Initial time
tstart = seconds(8.9);
% Ending time
tend = tstart + seconds(1);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);

filt_amplZ = 3; % g

ii = 1;
while Orig_1.Z1(ii) <= filt_amplZ
        ii = ii + 1;
end
tstart = Orig_1.Time(ii);
tend = tstart + seconds(0.4);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2")

plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2")

plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2")
```

Lowpass Filter for the Shots

```
filt_freq = 500;  % HZ

figure
lowpass(Orig_1(:,"X1"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_1(:,"Y1"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_1(:,"Z1"),filt_freq,'Steepness',0.99)

Orig_1_f = lowpass(Orig_1,filt_freq,'Steepness',0.99);

figure
lowpass(Orig_2(:,"X2"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_2(:,"Y2"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_2(:,"Z2"),filt_freq,'Steepness',0.99)

Orig_2_f = lowpass(Orig_2,filt_freq,'Steepness',0.99);

figure
stackedplot(Orig_1_f)
title("Temporal Response First Shot - Filtered")
xlabel("Time [s]")
```

```
figure
stackedplot(Orig_2_f)
title("Temporal Response Second Shot - Filtered")
xlabel("Time [s]")
```

Rainflow counting method for the filtered signal

```
[c_X1,rm_X1,rmr_X1,rmm_X1] = rainflow(Orig_1_f(:,"X1"));
[c_X2,rm_X2,rmr_X2,rmm_X2] = rainflow(Orig_2_f(:,"X2"));

[c_Y1,rm_Y1,rmr_Y1,rmm_Y1] = rainflow(Orig_1_f(:,"Y1"));
[c_Y2,rm_Y2,rmr_Y2,rmm_Y2] = rainflow(Orig_2_f(:,"Y2"));

[c_Z1,rm_Z1,rmr_Z1,rmm_Z1] = rainflow(Orig_1_f(:,"Z1"));
[c_Z2,rm_Z2,rmr_Z2,rmm_Z2] = rainflow(Orig_2_f(:,"Z2"));

histogram('BinEdges',rmr_X1','BinCounts',sum(rm_X1,2))
hold on
histogram('BinEdges',rmr_Y1','BinCounts',sum(rm_Y1,2))
histogram('BinEdges',rmr_Z1','BinCounts',sum(rm_Z1,2))
hold off
title('First Shot (Filtered)')
xlabel('Stress Range')
ylabel('Cycle Counts')
legend('X1','Y1','Z1')

histogram('BinEdges',rmr_X2','BinCounts',sum(rm_X2,2))
hold on
histogram('BinEdges',rmr_Y2','BinCounts',sum(rm_Y2,2))
histogram('BinEdges',rmr_Z2','BinCounts',sum(rm_Z2,2))
hold off
title('Second Shot (Filtered)')
xlabel('Stress Range')
ylabel('Cycle Counts')
legend('X2','Y2','Z2')
```

Equivalent damage for Rainflow calculations

```
Sz = size(rmr_X1,1);
Sm = sum(rm_X1,2);
Cc = rmr_X1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_X1 = sum(Dg);

Sz = size(rmr_X2,1);
Sm = sum(rm_X2,2);
Cc = rmr_X2;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_X2 = sum(Dg);

Sz = size(rmr_Y1,1);
Sm = sum(rm_Y1,2);
Cc = rmr_Y1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Y1 = sum(Dg);

Sz = size(rmr_Y2,1);
Sm = sum(rm_Y2,2);
Cc = rmr_Y2;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Y2 = sum(Dg);

Sz = size(rmr_Z1,1);
Sm = sum(rm_Z1,2);
Cc = rmr_Z1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
```

```
Damage_Z1 = sum(Dg);

Sz = size(rmr_Z2,1);
Sm = sum(rm_Z2,2);
Cc = rmr_Z2;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Z2 = sum(Dg);
```

Signal Statisics in Local Coordinate System

```
P2P_X1 = peak2peak(Orig_1_f.X1);
P2P_X2 = peak2peak(Orig_2_f.X2);

P2P_Y1 = peak2peak(Orig_1_f.Y1);
P2P_Y2 = peak2peak(Orig_2_f.Y2);

P2P_Z1 = peak2peak(Orig_1_f.Z1);
P2P_Z2 = peak2peak(Orig_2_f.Z2);

RMS_X1 = rms(Orig_1_f.X1);
RMS_X2 = rms(Orig_2_f.X2);

RMS_Y1 = rms(Orig_1_f.Y1);
RMS_Y2 = rms(Orig_2_f.Y2);

RMS_Z1 = rms(Orig_1_f.Z1);
RMS_Z2 = rms(Orig_2_f.Z2);
```

Signal Statistics in Global Coordinate System

```
% local X --> global Y with a counterclockwise angle of 24 deg.
% local Y --> global Z
% local Z --> global X with a counterclockwise angle of 24 deg.

Ang = 24 * pi / 180; % angle in radians

P2P_X1_G = cos(Ang) * P2P_Z1 - sin(Ang) * P2P_X1;
P2P_X2_G = cos(Ang) * P2P_Z2 - sin(Ang) * P2P_X2;

P2P_Y1_G = sin(Ang) * P2P_Z1 + cos(Ang) * P2P_X1;
P2P_Y2_G = sin(Ang) * P2P_Z2 + cos(Ang) * P2P_X2;

P2P_Z1_G = P2P_Y1;
P2P_Z2_G = P2P_Y2;

RMS_X1_G = cos(Ang) * RMS_Z1 - sin(Ang) * RMS_X1;
RMS_X2_G = cos(Ang) * RMS_Z2 - sin(Ang) * RMS_X2;

RMS_Y1_G = sin(Ang) * RMS_Z1 + cos(Ang) * RMS_X1;
RMS_Y2_G = sin(Ang) * RMS_Z2 + cos(Ang) * RMS_X2;

RMS_Z1_G = RMS_Y1;
RMS_Z2_G = RMS_Y2;

Dam_X1_G = cos(Ang) * Damage_Z1 - sin(Ang) * Damage_X1;
Dam_X2_G = cos(Ang) * Damage_Z2 - sin(Ang) * Damage_X2;

Dam_Y1_G = sin(Ang) * Damage_Z1 + cos(Ang) * Damage_X1;
Dam_Y2_G = sin(Ang) * Damage_Z2 + cos(Ang) * Damage_X2;

Dam_Z1_G = Damage_Y1;
Dam_Z2_G = Damage_Y2;
```

Print the output

```
vp.a = [P2P_X1_G P2P_X2_G;P2P_Y1_G P2P_Y2_G;P2P_Z1_G P2P_Z2_G];
vp.b = [RMS_X1_G RMS_X2_G;RMS_Y1_G RMS_Y2_G;RMS_Z1_G RMS_Z2_G];
vp.c = [Dam_X1_G Dam_X2_G;Dam_Y1_G Dam_Y2_G;Dam_Z1_G Dam_Z2_G];

save(['Pos1-200-0-A.txt'],'-struct','vp','-ascii')
```

Microphone analysis – Configuration 200-0-A

Reading of the Excel spreadsheet and creation of timetables

```
close all;
clear;
clc;

% Time Step
Tstep = 0.000078125;

Orig = readtimetable("MIC-200-0-A.xlsx","TimeStep",seconds(Tstep));
```

Plotting of the three signals

```
figure
plot(Orig.Time,Orig.T1)
hold on
plot(Orig.Time,Orig.T2)
plot(Orig.Time,Orig.T3)
hold off
title("Pressure sound")
xlabel("Time [s]")
ylabel("Pressure sound [Pa]")
legend("Test 1","Test 2","Test 3",'location','southeast')

%{
h = plot(1:10,1:10,1:10,2:11);
c = get(h,'Color')
c{1}
c{2}
%}
```

Redemensioning of the timetable

```
Orig_1 = Orig(:,"T1");
Orig_2 = Orig(:,"T2");
Orig_3 = Orig(:,"T3");

%{
% Emergency re-demensioning
tstart = seconds(6);    % Initial time
tend = Orig.Time(end);  % Ending time
timeLimits = timerange(tstart,tend);
Orig_2 = Orig_2(timeLimits,:);
%}

[pks1,locs] = findpeaks(Orig_1.T1);
[Max_pks1,Ind] = max(pks1);
tstart1 = Orig_1.Time(locs(Ind));

tstart1 = tstart1 - seconds(0.1);  % Initial time
tend1 = tstart1 + seconds(0.5);    % Ending time
timeLimits1 = timerange(tstart1,tend1);
Orig_1 = Orig_1(timeLimits1,:);

[pks2,locs] = findpeaks(Orig_2.T2);
[Max_pks2,Ind] = max(pks2);
tstart2 = Orig_2.Time(locs(Ind));

tstart2 = tstart2 - seconds(0.1);  % Initial time
tend2 = tstart2 + seconds(0.5);    % Ending time
timeLimits2 = timerange(tstart2,tend2);
Orig_2 = Orig_2(timeLimits2,:);

[pks3,locs] = findpeaks(Orig_3.T3);
[Max_pks3,Ind] = max(pks3);
tstart3 = Orig_3.Time(locs(Ind));

tstart3 = tstart3 - seconds(0.1);  % Initial time
tend3 = tstart3 + seconds(0.5);    % Ending time
timeLimits3 = timerange(tstart3,tend3);
Orig_3 = Orig_3(timeLimits3,:);

figure
plot(Orig_1.Time,Orig_1.T1)
title("Pressure sound - 1st shot")
xlabel("Time [s]")
ylabel("Pressure sound [Pa]")

figure
plot(Orig_2.Time,Orig_2.T2)
title("Pressure sound - 2nd shot")
xlabel("Time [s]")
ylabel("Pressure sound [Pa]")

figure
plot(Orig_3.Time,Orig_3.T3)
title("Pressure sound - 3rd shot")
xlabel("Time [s]")
ylabel("Pressure sound [Pa]")

tiledlayout(3,1)

% Top plot
ax1 = nexttile;
plot(ax1,Orig_1.Time,Orig_1.T1)
ylim([-15 10])
title(ax1,'Pressure sound - 1st shot')
%xlabel(ax1,'Time [s]')
```

```
%ylabel(ax1,'Pressure sound [Pa]')
% Middle plot
ax2 = nexttile;
plot(ax2,Orig_2.Time,Orig_2.T2)
ylim([-15 10])
title(ax2,'Pressure sound - 2nd shot')
%xlabel(ax2,'Time [s]')
ylabel(ax2,'Pressure sound [Pa]')
% Bottom plot
ax3 = nexttile;
plot(ax3,Orig_3.Time,Orig_3.T3)
ylim([-15 10])
title(ax3,'Pressure sound - 3rd shot')
xlabel(ax3,'Time [s]')
%ylabel(ax3,'Pressure sound [Pa])')
```

A-Weighting Filter

```
%{
wF1 = weightingFilter;
%wF2 = weightingFilter('C-weighting');
%wF3 = weightingFilter('K-weighting');

%fvt = fvtool(wF1,wF2,wF3,'FrequencyScale','Log','Fs',wF1.SampleRate);
fvt = fvtool(wF1,'FrequencyScale','Log','Fs',wF1.SampleRate);
%legend(fvt,'A-weighting','C-weighting','K-weighting',Location="best")
legend(fvt,'A-weighting',Location="best")
%}
```

Filtering of the signal according to an A-weighting filter: is a bandpass filter designed to simulate the perceived loudness of low-level tones. An A-weighting filter progressively de-emphasises frequencies below 500 Hz.

```
Fs = 1 / Tstep;
AWeighting = weightingFilter('A-weighting',Fs);
Orig_1f.T1 = AWeighting(Orig_1.T1);
Orig_2f.T2 = AWeighting(Orig_2.T2);
Orig_3f.T3 = AWeighting(Orig_3.T3);
```

Sound signals in dB

```
SPL.T1 = spl(Orig_1.T1,'air',0.05,Fs);
t1 = cumsum(ones(size(Orig_1.T1))/Fs);
Max_T1 = max(SPL.T1);
Avg_T1 = spl(Orig_1.T1,'air');

SPLf.T1 = spl(Orig_1f.T1,'air',0.05,Fs);
t1f = cumsum(ones(size(Orig_1f.T1))/Fs);
Maxf_T1 = max(SPLf.T1);
Avgf_T1 = spl(Orig_1f.T1,'air');

figure
subplot(3,1,1)
plot(t1,Orig_1.T1)
axis tight
xlabel(' ')
ylabel('Pressure [Pa]')
title('Sound Pressure - 1st shot - Original')
subplot(3,1,2)
plot(t1f,Orig_1f.T1,'Color',[0.85 0.325 0.098])
axis tight
ylabel('Pressure [Pa]')
title('Sound Pressure - 1st shot - Filtered')
subplot(3,1,3)
hold on
plot(t1,SPL.T1)
plot(t1f,SPLf.T1,'Color',[0.85 0.325 0.098])
hold off
axis tight
ylabel('SPL [dB]')
xlabel('Time [s]')
legend("Original","Filtered")

SPL.T2 = spl(Orig_2.T2,'air',0.05,Fs);
t2 = cumsum(ones(size(Orig_2.T2))/Fs);
Max_T2 = max(SPL.T2);
Avg_T2 = spl(Orig_2.T2,'air');

SPLf.T2 = spl(Orig_2f.T2,'air',0.05,Fs);
t2f = cumsum(ones(size(Orig_2f.T2))/Fs);
Maxf_T2 = max(SPLf.T2);
Avgf_T2 = spl(Orig_2f.T2,'air');

figure
subplot(2,1,1)
hold on
plot(t2,Orig_2.T2)
plot(t2f,Orig_2f.T2)
hold off
```

```
axis tight
ylabel('Pressure [Pa]')
title('Sound Pressure - 2nd shot')
legend("Original","Filtered")
subplot(2,1,2)
hold on
plot(t2,SPL.T2)
plot(t2f,SPLf.T2)
hold off
axis tight
ylabel('SPL [dB]')
xlabel('Time [s]')
legend("Original","Filtered")

SPL.T3 = spl(Orig_3.T3,'air',0.05,Fs);
t3 = cumsum(ones(size(Orig_3.T3))/Fs);
Max_T3 = max(SPL.T3);
Avg_T3 = spl(Orig_3.T3,'air');

SPLf.T3 = spl(Orig_3f.T3,'air',0.05,Fs);
t3f = cumsum(ones(size(Orig_3f.T3))/Fs);
Maxf_T3 = max(SPLf.T3);
Avgf_T3 = spl(Orig_3f.T3,'air');

figure
subplot(2,1,1)
hold on
plot(t3,Orig_3.T3)
plot(t3f,Orig_3f.T3)
hold off
axis tight
ylabel('Pressure [Pa]')
title('Sound Pressure - 3rd shot')
legend("Original","Filtered")
subplot(2,1,2)
hold on
plot(t3,SPL.T3)
plot(t3f,SPLf.T3)
hold off
axis tight
ylabel('SPL [dB]')
xlabel('Time [s]')
legend("Original","Filtered")
```

Power spectrum of the original and filtered signals

```
[pwr_T1,freq_T1] = pspectrum(Orig_1.T1,Fs);
[pwrf_T1,freqf_T1] = pspectrum(Orig_1f.T1,Fs);

[pwr_T2,freq_T2] = pspectrum(Orig_2.T2,Fs);
[pwrf_T2,freqf_T2] = pspectrum(Orig_2f.T2,Fs);

[pwr_T3,freq_T3] = pspectrum(Orig_3.T3,Fs);
[pwrf_T3,freqf_T3] = pspectrum(Orig_3f.T3,Fs);

p_0 = 20e-6;  % Reference pressure N/m2

pwr_dB_T1 = 10*log10(pwr_T1 / p_0^2);
pwr_dB_T2 = 10*log10(pwr_T2 / p_0^2);
pwr_dB_T3 = 10*log10(pwr_T3 / p_0^2);

pwrf_dB_T1 = 10*log10(pwrf_T1 / p_0^2);
pwrf_dB_T2 = 10*log10(pwrf_T2 / p_0^2);
pwrf_dB_T3 = 10*log10(pwrf_T3 / p_0^2);

figure
semilogx(freq_T1,pwr_T1)
hold on
semilogx(freqf_T1,pwrf_T1)
hold off
title("Power Spectrum - 1st shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [Pa^2]")
legend("Original","Filtered")

figure
semilogx(freq_T1,pwr_dB_T1)
hold on
semilogx(freqf_T1,pwrf_dB_T1)
hold off
title("Power Spectrum - 1st shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
legend("Original","Filtered",'Location','southwest')
grid on
```

```
figure
semilogx(freq_T2,pwr_T2)
hold on
semilogx(freqf_T2,pwrf_T2)
hold off
title("Power Spectrum - 2nd shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [Pa^2]")
legend("Original","Filtered")

figure
semilogx(freq_T2,pwr_dB_T2)
hold on
semilogx(freqf_T2,pwrf_dB_T2)
hold off
title("Power Spectrum - 2nd shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
legend("Original","Filtered",'Location','southwest')

figure
semilogx(freq_T3,pwr_T3)
hold on
semilogx(freqf_T3,pwrf_T3)
hold off
title("Power Spectrum - 3rd shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [Pa^2]")
legend("Original","Filtered")

figure
semilogx(freq_T3,pwr_dB_T3)
hold on
semilogx(freqf_T3,pwrf_dB_T3)
hold off
title("Power Spectrum - 3rd shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
legend("Original","Filtered",'Location','southwest')

figure
semilogx(freqf_T1,pwrf_T1)
hold on
semilogx(freqf_T2,pwrf_T2)
semilogx(freqf_T3,pwrf_T3)
hold off
title("Power Spectrum - A-Filtered shots")
xlabel("Frequency [Hz]")
ylabel("Sound Pressure Level [Pa^2]")
legend("1st shot","2nd shot","3rd shot",'location','northwest')

figure
semilogx(freqf_T1,pwrf_dB_T1)
hold on
semilogx(freqf_T2,pwrf_dB_T2)
semilogx(freqf_T3,pwrf_dB_T3)
hold off
title("Power Spectrum - A-Filtered shots")
xlabel("Frequency [Hz]")
ylabel("Sound Pressure Level [dB]")
legend("1st shot","2nd shot","3rd shot",'location','southwest')
```

Signals Statistics:
1. Maximum peak in dB (Maxf_T1)
2. SPL of the A-weighted filtered signal in dB (the reference time is 0.5 s) (Avgf_T1)
3. Energy Equivalent Continuous Sound Level (Leq_T1)

```
% p_0 = 20e-6;  % N/m2

p_ref_T1 = rms(Orig_1f.T1);
Leq_T1 = 20 * log10(p_ref_T1 / p_0);

p_ref_T2 = rms(Orig_2f.T2);
Leq_T2 = 20 * log10(p_ref_T2 / p_0);

p_ref_T3 = rms(Orig_3f.T3);
Leq_T3 = 20 * log10(p_ref_T3 / p_0);
```

Print the output

```
vp.a = [Maxf_T1;Maxf_T2;Maxf_T3];
vp.b = [Avgf_T1;Avgf_T2;Avgf_T3];
vp.c = [Leq_T1;Leq_T2;Leq_T3];

save('MIC-200-0-A.txt','-struct','vp','-ascii')
```

Matlab scripts for the third paper.

Vibration analysis – Position 1 – Axia Formula (AXF)

Reading of the Excel spreadsheet and creation of timetables

```
close all;
clf;
clear;

% Time Step
Tstep = 0.000078125;

Orig = readtimetable("Pos1-AXF.xlsx","TimeStep",seconds(Tstep));
```

Plotting of the three responses

```
figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northwest')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northwest')
```

Initial redemensioning of the timetable

```
% Initial time
tstart = seconds(7);
% Ending time
tend = Orig.Time(end);
timeLimits = timerange(tstart,tend);
Orig = Orig(timeLimits,:);

figure
plot(Orig.Time,Orig.X1)
hold on
plot(Orig.Time,Orig.X2)
plot(Orig.Time,Orig.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3",'location','northeast')

plot(Orig.Time,Orig.Y1)
hold on
plot(Orig.Time,Orig.Y2)
plot(Orig.Time,Orig.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northeast')

plot(Orig.Time,Orig.Z1)
hold on
plot(Orig.Time,Orig.Z2)
plot(Orig.Time,Orig.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
```

```
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3",'location','northeast')
```

Alignment of the signals

```
Orig_1 = Orig(:,["X1","Y1","Z1"]);
Orig_2 = Orig(:,["X2","Y2","Z2"]);
Orig_3 = Orig(:,["X3","Y3","Z3"]);

X2Delay = finddelay(Orig.X1,Orig.X2);
X2Delay = seconds(X2Delay*Tstep);
Orig_2.Properties.StartTime = -X2Delay + tstart;

X3Delay = finddelay(Orig.X1,Orig.X3);
X3Delay = seconds(X3Delay*Tstep);
Orig_3.Properties.StartTime = -X3Delay + tstart;

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
plot(Orig_3.Time,Orig_3.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3")

plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3")

plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
plot(Orig_3.Time,Orig_3.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3")
```

Redemensioning of the timetable

```
% Initial time
tstart = seconds(9.5);
% Ending time
tend = tstart + seconds(1);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);

filt_amplZ = 3; % g

ii = 1;
while Orig_1.Z1(ii) <= filt_amplZ
        ii = ii + 1;
end
tstart = Orig_1.Time(ii);
tend = tstart + seconds(0.4);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);

plot(Orig_1.Time,Orig_1.X1)
hold on
plot(Orig_2.Time,Orig_2.X2)
plot(Orig_3.Time,Orig_3.X3)
hold off
title("Acceleration X-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("X1","X2","X3")

plot(Orig_1.Time,Orig_1.Y1)
hold on
```

```
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3")

plot(Orig_1.Time,Orig_1.Z1)
hold on
plot(Orig_2.Time,Orig_2.Z2)
plot(Orig_3.Time,Orig_3.Z3)
hold off
title("Acceleration Z-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Z1","Z2","Z3")
```

Temporal Response

```
figure
stackedplot(Orig_1)
title("Temporal Response - First Shot")
xlabel("Time [s]")

figure
stackedplot(Orig_2)
title("Temporal Response - Second Shot")
xlabel("Time [s]")

figure
stackedplot(Orig_3)
title("Temporal Response - Third Shot")
xlabel("Time [s]")
```

Creation of the power spectrum of the signals of the First Shot

```
max_freq = 4000; % Hz

tiledlayout(3,1)
nexttile
pspectrum(Orig_1(:,"X1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - X Direction")
nexttile
pspectrum(Orig_1(:,"Y1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - Y Direction")
nexttile
pspectrum(Orig_1(:,"Z1"),"FrequencyLimits",[0 max_freq])
title("Power Spectrum - Z Direction")

figure
[pwr_X,freq_X] = pspectrum(Orig_1(:,"X1"));
semilogx(freq_X,db(pwr_X,"power"))
title("Power Spectrum - X-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")

[pwr_Y,freq_Y] = pspectrum(Orig_1(:,"Y1"));
semilogx(freq_Y,db(pwr_Y,"power"))
title("Power Spectrum - Y-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")

[pwr_Z,freq_Z] = pspectrum(Orig_1(:,"Z1"));
semilogx(freq_Z,db(pwr_Z,"power"))
title("Power Spectrum - Z-direction")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
```

Signal Statistics in Local Coordinate System

```
P2P_X1 = peak2peak(Orig_1.X1);
P2P_X2 = peak2peak(Orig_2.X2);
P2P_X3 = peak2peak(Orig_3.X3);

P2P_Y1 = peak2peak(Orig_1.Y1);
P2P_Y2 = peak2peak(Orig_2.Y2);
P2P_Y3 = peak2peak(Orig_3.Y3);

P2P_Z1 = peak2peak(Orig_1.Z1);
P2P_Z2 = peak2peak(Orig_2.Z2);
P2P_Z3 = peak2peak(Orig_3.Z3);

RMS_X1 = rms(Orig_1.X1);
RMS_X2 = rms(Orig_2.X2);
RMS_X3 = rms(Orig_3.X3);

RMS_Y1 = rms(Orig_1.Y1);
```

```
RMS_Y2 = rms(Orig_2.Y2);
RMS_Y3 = rms(Orig_3.Y3);

RMS_Z1 = rms(Orig_1.Z1);
RMS_Z2 = rms(Orig_2.Z2);
RMS_Z3 = rms(Orig_3.Z3);
```

Signal Statistics in Global Coordinate System

```
% local X --> global Y with a counterclockwise angle of 28 deg.
% local Y --> global Z
% local Z --> global X with a counterclockwise angle of 28 deg.

Ang = 28 * pi / 180; % angle in radians

P2P_X1_G = peak2peak(- cos(Ang) * Orig_1.Z1 - sin(Ang) * Orig_1.X1);
P2P_X2_G = peak2peak(- cos(Ang) * Orig_2.Z2 - sin(Ang) * Orig_2.X2);
P2P_X3_G = peak2peak(- cos(Ang) * Orig_3.Z3 - sin(Ang) * Orig_3.X3);

P2P_Y1_G = peak2peak(- sin(Ang) * Orig_1.Z1 + cos(Ang) * Orig_1.X1);
P2P_Y2_G = peak2peak(- sin(Ang) * Orig_2.Z2 + cos(Ang) * Orig_2.X2);
P2P_Y3_G = peak2peak(- sin(Ang) * Orig_3.Z3 + cos(Ang) * Orig_3.X3);

P2P_Z1_G = P2P_Y1;
P2P_Z2_G = P2P_Y2;
P2P_Z3_G = P2P_Y3;

RMS_X1_G = rms(- cos(Ang) * Orig_1.Z1 - sin(Ang) * Orig_1.X1);
RMS_X2_G = rms(- cos(Ang) * Orig_2.Z2 - sin(Ang) * Orig_2.X2);
RMS_X3_G = rms(- cos(Ang) * Orig_3.Z3 - sin(Ang) * Orig_3.X3);

RMS_Y1_G = rms(- sin(Ang) * Orig_1.Z1 + cos(Ang) * Orig_1.X1);
RMS_Y2_G = rms(- sin(Ang) * Orig_2.Z2 + cos(Ang) * Orig_2.X2);
RMS_Y3_G = rms(- sin(Ang) * Orig_3.Z3 + cos(Ang) * Orig_3.X3);

RMS_Z1_G = RMS_Y1;
RMS_Z2_G = RMS_Y2;
RMS_Z3_G = RMS_Y3;
```

Print the output

```
vp.a = [P2P_X1_G P2P_X2_G P2P_X3_G;P2P_Y1_G P2P_Y2_G P2P_Y3_G;P2P_Z1_G P2P_Z2_G P2P_Z3_G];
vp.b = [RMS_X1_G RMS_X2_G RMS_X3_G;RMS_Y1_G RMS_Y2_G RMS_Y3_G;RMS_Z1_G RMS_Z2_G RMS_Z3_G];

save('Pos1-AXF.txt','-struct','vp','-ascii')
```

Decay Time analysis – Position 1

Reading of the Excel spreadsheet and creation of timetables

```
close all;
clf;
clear;

% Time Step
Tstep = 0.000078125;

for jj = 1:9

    if jj == 1
        Orig = readtimetable("Pos1-MC5.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(9.1);
    elseif jj == 2
        Orig = readtimetable("Pos1-NSF.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(9.4);
    elseif jj == 3
        Orig = readtimetable("Pos1-NSW.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(11.5);
    elseif jj == 4
        Orig = readtimetable("Pos1-UUK.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(9.3);
    elseif jj == 5
        Orig = readtimetable("Pos1-CAV.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(7.85);
    elseif jj == 6
        Orig = readtimetable("Pos1-MXF.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(9.1);
    elseif jj == 7
        Orig = readtimetable("Pos1-MXW.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(9);
    elseif jj == 8
        Orig = readtimetable("Pos1-AXI.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(10.8);
    elseif jj == 9
        Orig = readtimetable("Pos1-AXF.xlsx","TimeStep",seconds(Tstep));
        start_time = seconds(9.5);
    end
```

The timetable is reduced according to the defined cutting time

```
Orig_1 = Orig(:,["X1","Y1","Z1"]);
Orig_2 = Orig(:,["X2","Y2","Z2"]);
Orig_3 = Orig(:,["X3","Y3","Z3"]);

Y2Delay = finddelay(Orig.Y1,Orig.Y2);
Y2Delay = seconds(Y2Delay*Tstep);
Orig_2.Properties.StartTime = -Y2Delay;

Y3Delay = finddelay(Orig.Y1,Orig.Y3);
Y3Delay = seconds(Y3Delay*Tstep);
Orig_3.Properties.StartTime = -Y3Delay;

%{
plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northwest')
%}
% End time
end_time_1 = Orig_1.Time(end);
end_time_2 = Orig_2.Time(end);
end_time_3 = Orig_3.Time(end);

end_time = min([end_time_1 end_time_2 end_time_3]);

timeLimits = timerange(start_time,end_time);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);

%{
plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northeast')
%}
```

Filtering of the data

```
P2P_Y1 = peak2peak(Orig_1.Y1);
P2P_Y2 = peak2peak(Orig_2.Y2);
P2P_Y3 = peak2peak(Orig_3.Y3);

P2P_Y = max([P2P_Y1 P2P_Y2 P2P_Y3]);

filt_ampl = P2P_Y * 0.05;  % 5% of the original amplitude of the signal [g]
Size_Orig_1 = size(Orig_1,1);

for ii = 1:Size_Orig_1
    if Orig_1.Y1(ii) <= filt_ampl
        Orig_1.Y1(ii) = 0;
    end
    if Orig_2.Y2(ii) <= filt_ampl
        Orig_2.Y2(ii) = 0;
    end
    if Orig_3.Y3(ii) <= filt_ampl
        Orig_3.Y3(ii) = 0;
    end
end

%{
plot(Orig_1.Time,Orig_1.Y1)
hold on
plot(Orig_2.Time,Orig_2.Y2)
plot(Orig_3.Time,Orig_3.Y3)
hold off
title("Acceleration Y-axis")
xlabel("Time [s]")
ylabel("Acceleration [g]")
legend("Y1","Y2","Y3",'location','northeast')
%}
```

Research of the starting time and end time of the event

```
ii = 1;
```

```
    while Orig_1.Y1(ii) == 0
        ii = ii + 1;
    end
    Y11 = Orig_1.Time(ii);
    ii = Size_Orig_1;
    while Orig_1.Y1(ii) == 0
        ii = ii - 1;
    end
    Y12 = Orig_1.Time(ii);
    DZ1 = seconds(Y12 - Y11);

    ii = 1;
    while Orig_2.Y2(ii) == 0
        ii = ii + 1;
    end
    Y21 = Orig_2.Time(ii);
    ii = Size_Orig_1;
    while Orig_2.Y2(ii) == 0
        ii = ii - 1;
    end
    Y22 = Orig_2.Time(ii);
    DZ2 = seconds(Y22 - Y21);

    ii = 1;
    while Orig_3.Y3(ii) == 0
        ii = ii + 1;
    end
    Y31 = Orig_3.Time(ii);
    ii = Size_Orig_1;
    while Orig_3.Y3(ii) == 0
        ii = ii - 1;
    end
    Y32 = Orig_3.Time(ii);
    DZ3 = seconds(Y32 - Y31);
```

Saving of the results

```
    Res = [DZ1; DZ2; DZ3];

    if jj == 1
        save('Pos1_Decay_Time.txt','Res','-ascii')
    else
        save('Pos1_Decay_Time.txt','Res','-ascii','-append')
    end

end
```

Vibration analysis – Position 1 – Axia Formula (AXF) – Filtered data

Reading of the Excel spreadsheet and creation of timetables

```
close all;
clf;
clear;

% Time Step
Tstep = 0.000078125;

Orig = readtimetable("Pos1-AXF.xlsx","TimeStep",seconds(Tstep));
```

Alignment of the signals

```
Orig_1 = Orig(:,["X1","Y1","Z1"]);
Orig_2 = Orig(:,["X2","Y2","Z2"]);
Orig_3 = Orig(:,["X3","Y3","Z3"]);

X2Delay = finddelay(Orig.X1,Orig.X2);
X2Delay = seconds(X2Delay*Tstep);
Orig_2.Properties.StartTime = -X2Delay;

X3Delay = finddelay(Orig.X1,Orig.X3);
X3Delay = seconds(X3Delay*Tstep);
Orig_3.Properties.StartTime = -X3Delay;
```

Redemensioning of the timetable

```
% Initial time
tstart = seconds(9.5);
% Ending time
tend = tstart + seconds(1);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);
```

```
filt_amplZ = 3; % g

ii = 1;
while Orig_1.Z1(ii) <= filt_amplZ
        ii = ii + 1;
end
tstart = Orig_1.Time(ii);
tend = tstart + seconds(0.4);

timeLimits = timerange(tstart,tend);

Orig_1 = Orig_1(timeLimits,:);
Orig_2 = Orig_2(timeLimits,:);
Orig_3 = Orig_3(timeLimits,:);
```

Lowpass Filter for the Shots

```
filt_freq = 500;  % HZ

figure
lowpass(Orig_1(:,"X1"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_1(:,"Y1"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_1(:,"Z1"),filt_freq,'Steepness',0.99)

Orig_1_f = lowpass(Orig_1,filt_freq,'Steepness',0.99);

figure
lowpass(Orig_2(:,"X2"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_2(:,"Y2"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_2(:,"Z2"),filt_freq,'Steepness',0.99)

Orig_2_f = lowpass(Orig_2,filt_freq,'Steepness',0.99);

figure
lowpass(Orig_3(:,"X3"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_3(:,"Y3"),filt_freq,'Steepness',0.99)
figure
lowpass(Orig_3(:,"Z3"),filt_freq,'Steepness',0.99)

Orig_3_f = lowpass(Orig_3,filt_freq,'Steepness',0.99);

figure
stackedplot(Orig_1_f)
title("Temporal Response First Shot - Filtered")
xlabel("Time [s]")

figure
stackedplot(Orig_2_f)
title("Temporal Response Second Shot - Filtered")
xlabel("Time [s]")

figure
stackedplot(Orig_3_f)
title("Temporal Response Third Shot - Filtered")
xlabel("Time [s]")
```

Rainflow counting method for the filtered signal

```
[c_X1,rm_X1,rmr_X1,rmm_X1] = rainflow(Orig_1_f(:,"X1"));
[c_X2,rm_X2,rmr_X2,rmm_X2] = rainflow(Orig_2_f(:,"X2"));
[c_X3,rm_X3,rmr_X3,rmm_X3] = rainflow(Orig_3_f(:,"X3"));

[c_Y1,rm_Y1,rmr_Y1,rmm_Y1] = rainflow(Orig_1_f(:,"Y1"));
[c_Y2,rm_Y2,rmr_Y2,rmm_Y2] = rainflow(Orig_2_f(:,"Y2"));
[c_Y3,rm_Y3,rmr_Y3,rmm_Y3] = rainflow(Orig_3_f(:,"Y3"));

[c_Z1,rm_Z1,rmr_Z1,rmm_Z1] = rainflow(Orig_1_f(:,"Z1"));
[c_Z2,rm_Z2,rmr_Z2,rmm_Z2] = rainflow(Orig_2_f(:,"Z2"));
[c_Z3,rm_Z3,rmr_Z3,rmm_Z3] = rainflow(Orig_3_f(:,"Z3"));

histogram('BinEdges',rmr_X1','BinCounts',sum(rm_X1,2))
hold on
histogram('BinEdges',rmr_Y1','BinCounts',sum(rm_Y1,2))
histogram('BinEdges',rmr_Z1','BinCounts',sum(rm_Z1,2))
hold off
title('First Shot (Filtered)')
xlabel('Stress Range')
ylabel('Cycle Counts')
legend('X1','Y1','Z1')

histogram('BinEdges',rmr_X2','BinCounts',sum(rm_X2,2))
hold on
```

```
histogram('BinEdges',rmr_Y2','BinCounts',sum(rm_Y2,2))
histogram('BinEdges',rmr_Z2','BinCounts',sum(rm_Z2,2))
hold off
title('Second Shot (Filtered)')
xlabel('Stress Range')
ylabel('Cycle Counts')
legend('X2','Y2','Z2')

histogram('BinEdges',rmr_X3','BinCounts',sum(rm_X3,2))
hold on
histogram('BinEdges',rmr_Y3','BinCounts',sum(rm_Y3,2))
histogram('BinEdges',rmr_Z3','BinCounts',sum(rm_Z3,2))
hold off
title('Second Shot (Filtered)')
xlabel('Stress Range')
ylabel('Cycle Counts')
legend('X3','Y3','Z3')
```

Equivalent damage for Rainflow calculations

```
Sz = size(rmr_X1,1);
Sm = sum(rm_X1,2);
Cc = rmr_X1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_X1 = sum(Dg);

Sz = size(rmr_X2,1);
Sm = sum(rm_X2,2);
Cc = rmr_X2;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_X2 = sum(Dg);

Sz = size(rmr_X3,1);
Sm = sum(rm_X3,2);
Cc = rmr_X3;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_X3 = sum(Dg);

Sz = size(rmr_Y1,1);
Sm = sum(rm_Y1,2);
Cc = rmr_Y1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Y1 = sum(Dg);

Sz = size(rmr_Y2,1);
Sm = sum(rm_Y2,2);
Cc = rmr_Y2;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Y2 = sum(Dg);

Sz = size(rmr_Y3,1);
Sm = sum(rm_Y3,2);
Cc = rmr_Y3;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Y3 = sum(Dg);

Sz = size(rmr_Z1,1);
Sm = sum(rm_Z1,2);
Cc = rmr_Z1;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
```

```
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Z1 = sum(Dg);

Sz = size(rmr_Z2,1);
Sm = sum(rm_Z2,2);
Cc = rmr_Z2;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Z2 = sum(Dg);

Sz = size(rmr_Z3,1);
Sm = sum(rm_Z3,2);
Cc = rmr_Z3;
Dg = zeros(50,1);
for ii = 2:Sz
    Avg = (Cc(ii) + Cc(ii-1))/2;
    Dg(ii) = Avg * Sm(ii-1);
end
Damage_Z3 = sum(Dg);
```

Signal Statistics in Global Coordinate System

```
% local X --> global Y with a counterclockwise angle of 28 deg.
% local Y --> global Z
% local Z --> global X with a counterclockwise angle of 28 deg.

Ang = 28 * pi / 180; % angle in radians

P2P_X1_G = peak2peak(- cos(Ang) * Orig_1_f.Z1 - sin(Ang) * Orig_1_f.X1);
P2P_X2_G = peak2peak(- cos(Ang) * Orig_2_f.Z2 - sin(Ang) * Orig_2_f.X2);
P2P_X3_G = peak2peak(- cos(Ang) * Orig_3_f.Z3 - sin(Ang) * Orig_3_f.X3);

P2P_Y1_G = peak2peak(- sin(Ang) * Orig_1_f.Z1 + cos(Ang) * Orig_1_f.X1);
P2P_Y2_G = peak2peak(- sin(Ang) * Orig_2_f.Z2 + cos(Ang) * Orig_2_f.X2);
P2P_Y3_G = peak2peak(- sin(Ang) * Orig_3_f.Z3 + cos(Ang) * Orig_3_f.X3);

P2P_Z1_G = peak2peak(Orig_1_f.Y1);
P2P_Z2_G = peak2peak(Orig_2_f.Y2);
P2P_Z3_G = peak2peak(Orig_3_f.Y3);

RMS_X1_G = rms(- cos(Ang) * Orig_1_f.Z1 - sin(Ang) * Orig_1_f.X1);
RMS_X2_G = rms(- cos(Ang) * Orig_2_f.Z2 - sin(Ang) * Orig_2_f.X2);
RMS_X3_G = rms(- cos(Ang) * Orig_3_f.Z3 - sin(Ang) * Orig_3_f.X3);

RMS_Y1_G = rms(- sin(Ang) * Orig_1_f.Z1 + cos(Ang) * Orig_1_f.X1);
RMS_Y2_G = rms(- sin(Ang) * Orig_2_f.Z2 + cos(Ang) * Orig_2_f.X2);
RMS_Y3_G = rms(- sin(Ang) * Orig_3_f.Z3 + cos(Ang) * Orig_3_f.X3);

RMS_Z1_G = rms(Orig_1_f.Y1);
RMS_Z2_G = rms(Orig_2_f.Y2);
RMS_Z3_G = rms(Orig_3_f.Y3);

Dam_X1_G = abs(- cos(Ang) * Damage_Z1 - sin(Ang) * Damage_X1);
Dam_X2_G = abs(- cos(Ang) * Damage_Z2 - sin(Ang) * Damage_X2);
Dam_X3_G = abs(- cos(Ang) * Damage_Z3 - sin(Ang) * Damage_X3);

Dam_Y1_G = abs(- sin(Ang) * Damage_Z1 + cos(Ang) * Damage_X1);
Dam_Y2_G = abs(- sin(Ang) * Damage_Z2 + cos(Ang) * Damage_X2);
Dam_Y3_G = abs(- sin(Ang) * Damage_Z3 + cos(Ang) * Damage_X3);

Dam_Z1_G = Damage_Y1;
Dam_Z2_G = Damage_Y2;
Dam_Z3_G = Damage_Y3;
```

Print the output

```
vp.a = [P2P_X1_G P2P_X2_G P2P_X3_G;P2P_Y1_G P2P_Y2_G P2P_Y3_G;P2P_Z1_G P2P_Z2_G P2P_Z3_G];
vp.b = [RMS_X1_G RMS_X2_G RMS_X3_G;RMS_Y1_G RMS_Y2_G RMS_Y3_G;RMS_Z1_G RMS_Z2_G RMS_Z3_G];
vp.c = [Dam_X1_G Dam_X2_G Dam_X3_G;Dam_Y1_G Dam_Y2_G Dam_Y3_G;Dam_Z1_G Dam_Z2_G Dam_Z3_G];

save('Pos1-AXF.txt','-struct','vp','-ascii')
```

Microphone analysis – Axia Formula (AXF)

Reading of the Excel spreadsheet and creation of timetables

```
close all;
clear;
clc;

% Time Step
Tstep = 0.0000390625;
```

```
Orig = readtimetable("Mic-AXF.xlsx","TimeStep",seconds(Tstep));
```

Plotting of the three signals

```
figure
plot(Orig.Time,Orig.S1)
hold on
plot(Orig.Time,Orig.S2)
plot(Orig.Time,Orig.S3)
hold off
title("Pressure sound")
xlabel("Time [s]")
ylabel("Pressure sound [Pa]")
legend("Test 1","Test 2","Test 3",'location','southeast')

%{
h = plot(1:10,1:10,1:10,2:11);
c = get(h,'Color')
c{1}
c{2}
%}
```

Redemensioning of the timetable

```
Orig_1 = Orig(:,"S1");
Orig_2 = Orig(:,"S2");
Orig_3 = Orig(:,"S3");

%{
% Emergency re-demensioning
tstart = seconds(6);    % Initial time
tend = Orig.Time(end);  % Ending time
timeLimits = timerange(tstart,tend);
Orig_2 = Orig_2(timeLimits,:);
%}

[pks1,locs] = findpeaks(Orig_1.S1);
[Max_pks1,Ind] = max(pks1);
tstart1 = Orig_1.Time(locs(Ind));

tstart1 = tstart1 - seconds(0.1);  % Initial time
tend1 = tstart1 + seconds(0.5);    % Ending time
timeLimits1 = timerange(tstart1,tend1);
Orig_1 = Orig_1(timeLimits1,:);

[pks2,locs] = findpeaks(Orig_2.S2);
[Max_pks2,Ind] = max(pks2);
tstart2 = Orig_2.Time(locs(Ind));

tstart2 = tstart2 - seconds(0.1);  % Initial time
tend2 = tstart2 + seconds(0.5);    % Ending time
timeLimits2 = timerange(tstart2,tend2);
Orig_2 = Orig_2(timeLimits2,:);

[pks3,locs] = findpeaks(Orig_3.S3);
[Max_pks3,Ind] = max(pks3);
tstart3 = Orig_3.Time(locs(Ind));

tstart3 = tstart3 - seconds(0.1);  % Initial time
tend3 = tstart3 + seconds(0.5);    % Ending time
timeLimits3 = timerange(tstart3,tend3);
Orig_3 = Orig_3(timeLimits3,:);

figure
plot(Orig_1.Time,Orig_1.S1)
title("Pressure sound - 1st shot")
xlabel("Time [s]")
ylabel("Pressure sound [Pa]")

figure
plot(Orig_2.Time,Orig_2.S2)
title("Pressure sound - 2nd shot")
xlabel("Time [s]")
ylabel("Pressure sound [Pa]")

figure
plot(Orig_3.Time,Orig_3.S3)
title("Pressure sound - 3rd shot")
xlabel("Time [s]")
ylabel("Pressure sound [Pa]")

tiledlayout(3,1)

% Top plot
ax1 = nexttile;
plot(ax1,Orig_1.Time,Orig_1.S1)
```

```
ylim([-15 15])
title(ax1,'Pressure Sound - 1st Shot')
%xlabel(ax1,'Time [s]')
%ylabel(ax1,'Pressure sound [Pa]')
% Middle plot
ax2 = nexttile;
plot(ax2,Orig_2.Time,Orig_2.S2)
ylim([-15 15])
title(ax2,'Pressure Sound - 2nd Shot')
%xlabel(ax2,'Time [s]')
ylabel(ax2,'Pressure sound [Pa]')
% Bottom plot
ax3 = nexttile;
plot(ax3,Orig_3.Time,Orig_3.S3)
ylim([-15 15])
title(ax3,'Pressure Sound - 3rd Shot')
xlabel(ax3,'Time [s]')
%ylabel(ax3,'Pressure sound [Pa])')
```

A-Weighting Filter

```
%{
wF1 = weightingFilter;
%wF2 = weightingFilter('C-weighting');
%wF3 = weightingFilter('K-weighting');

%fvt = fvtool(wF1,wF2,wF3,'FrequencyScale','Log','Fs',wF1.SampleRate);
fvt = fvtool(wF1,'FrequencyScale','Log','Fs',wF1.SampleRate);
%legend(fvt,'A-weighting','C-weighting','K-weighting',Location="best")
legend(fvt,'A-weighting',Location="best")
%}
```

Filtering of the signal according to an A-weighting filter: is a bandpass filter designed to simulate the perceived loudness of low-level tones. An A-weighting filter progressively de-emphasises frequencies below 500 Hz.

```
Fs = 1 / Tstep;
AWeighting = weightingFilter('A-weighting',Fs);
Orig_1f.S1 = AWeighting(Orig_1.S1);
Orig_2f.S2 = AWeighting(Orig_2.S2);
Orig_3f.S3 = AWeighting(Orig_3.S3);
```

Sound signals in dB

```
SPL.S1 = spl(Orig_1.S1,'air',0.05,Fs);
t1 = cumsum(ones(size(Orig_1.S1))/Fs);
Max_S1 = max(SPL.S1);
Avg_S1 = spl(Orig_1.S1,'air');

SPLf.S1 = spl(Orig_1f.S1,'air',0.05,Fs);
t1f = cumsum(ones(size(Orig_1f.S1))/Fs);
Maxf_S1 = max(SPLf.S1);
Avgf_S1 = spl(Orig_1f.S1,'air');

figure
subplot(3,1,1)
plot(t1,Orig_1.S1)
axis tight
xlabel(' ')
ylabel('Pressure [Pa]')
title('Sound Pressure - 1st shot - Original')
subplot(3,1,2)
plot(t1f,Orig_1f.S1,'Color',[0.85 0.325 0.098])
axis tight
ylabel('Pressure [Pa]')
title('Sound Pressure - 1st shot - Filtered')
subplot(3,1,3)
hold on
plot(t1,SPL.S1)
plot(t1f,SPLf.S1,'Color',[0.85 0.325 0.098])
hold off
axis tight
ylabel('SPL [dB]')
xlabel('Time [s]')
legend("Original","Filtered")

SPL.S2 = spl(Orig_2.S2,'air',0.05,Fs);
t2 = cumsum(ones(size(Orig_2.S2))/Fs);
Max_S2 = max(SPL.S2);
Avg_S2 = spl(Orig_2.S2,'air');

SPLf.S2 = spl(Orig_2f.S2,'air',0.05,Fs);
t2f = cumsum(ones(size(Orig_2f.S2))/Fs);
Maxf_S2 = max(SPLf.S2);
Avgf_S2 = spl(Orig_2f.S2,'air');

figure
subplot(2,1,1)
hold on
```

```
plot(t2,Orig_2.S2)
plot(t2f,Orig_2f.S2)
hold off
axis tight
ylabel('Pressure [Pa]')
title('Sound Pressure - 2nd shot')
legend("Original","Filtered")
subplot(2,1,2)
hold on
plot(t2,SPL.S2)
plot(t2f,SPLf.S2)
hold off
axis tight
ylabel('SPL [dB]')
xlabel('Time [s]')
legend("Original","Filtered")

SPL.S3 = spl(Orig_3.S3,'air',0.05,Fs);
t3 = cumsum(ones(size(Orig_3.S3))/Fs);
Max_S3 = max(SPL.S3);
Avg_S3 = spl(Orig_3.S3,'air');

SPLf.S3 = spl(Orig_3f.S3,'air',0.05,Fs);
t3f = cumsum(ones(size(Orig_3f.S3))/Fs);
Maxf_S3 = max(SPLf.S3);
Avgf_S3 = spl(Orig_3f.S3,'air');

figure
subplot(2,1,1)
hold on
plot(t3,Orig_3.S3)
plot(t3f,Orig_3f.S3)
hold off
axis tight
ylabel('Pressure [Pa]')
title('Sound Pressure - 3rd shot')
legend("Original","Filtered")
subplot(2,1,2)
hold on
plot(t3,SPL.S3)
plot(t3f,SPLf.S3)
hold off
axis tight
ylabel('SPL [dB]')
xlabel('Time [s]')
legend("Original","Filtered")
```

Power spectrum of the original and filtered signals

```
[pwr_S1,freq_S1] = pspectrum(Orig_1.S1,Fs);
[pwrf_S1,freqf_S1] = pspectrum(Orig_1f.S1,Fs);

[pwr_S2,freq_S2] = pspectrum(Orig_2.S2,Fs);
[pwrf_S2,freqf_S2] = pspectrum(Orig_2f.S2,Fs);

[pwr_S3,freq_S3] = pspectrum(Orig_3.S3,Fs);
[pwrf_S3,freqf_S3] = pspectrum(Orig_3f.S3,Fs);

p_0 = 20e-6;  % Reference pressure N/m2

pwr_dB_S1 = 10*log10(pwr_S1 / p_0^2);
pwr_dB_S2 = 10*log10(pwr_S2 / p_0^2);
pwr_dB_S3 = 10*log10(pwr_S3 / p_0^2);

pwrf_dB_S1 = 10*log10(pwrf_S1 / p_0^2);
pwrf_dB_S2 = 10*log10(pwrf_S2 / p_0^2);
pwrf_dB_S3 = 10*log10(pwrf_S3 / p_0^2);

figure
semilogx(freq_S1,pwr_S1)
hold on
semilogx(freqf_S1,pwrf_S1)
hold off
title("Power Spectrum - 1st shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [Pa^2]")
legend("Original","Filtered")

figure
semilogx(freq_S1,pwr_dB_S1)
hold on
semilogx(freqf_S1,pwrf_dB_S1)
hold off
title("Power Spectrum - 1st shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
```

```
legend("Original","Filtered",'Location','southwest')
grid on

figure
semilogx(freq_S2,pwr_S2)
hold on
semilogx(freqf_S2,pwrf_S2)
hold off
title("Power Spectrum - 2nd shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [Pa^2]")
legend("Original","Filtered")

figure
semilogx(freq_S2,pwr_dB_S2)
hold on
semilogx(freqf_S2,pwrf_dB_S2)
hold off
title("Power Spectrum - 2nd shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
legend("Original","Filtered",'Location','southwest')

figure
semilogx(freq_S3,pwr_S3)
hold on
semilogx(freqf_S3,pwrf_S3)
hold off
title("Power Spectrum - 3rd shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [Pa^2]")
legend("Original","Filtered")

figure
semilogx(freq_S3,pwr_dB_S3)
hold on
semilogx(freqf_S3,pwrf_dB_S3)
hold off
title("Power Spectrum - 3rd shot")
xlabel("Frequency [Hz]")
ylabel("Power Spectrum [dB]")
legend("Original","Filtered",'Location','southwest')

figure
semilogx(freqf_S1,pwrf_S1)
hold on
semilogx(freqf_S2,pwrf_S2)
semilogx(freqf_S3,pwrf_S3)
hold off
title("Power Spectrum - A-Filtered shots")
xlabel("Frequency [Hz]")
ylabel("Sound Pressure Level [Pa^2]")
legend("1st shot","2nd shot","3rd shot",'location','northwest')

figure
semilogx(freqf_S1,pwrf_dB_S1)
hold on
semilogx(freqf_S2,pwrf_dB_S2)
semilogx(freqf_S3,pwrf_dB_S3)
hold off
title("Power Spectrum - A-Filtered shots")
xlabel("Frequency [Hz]")
ylabel("Sound Pressure Level [dB]")
legend("1st shot","2nd shot","3rd shot",'location','southwest')
```

Signals Statistics:
1. Maximum peak in dB (Maxf_T1)
2. SPL of the A-weighted filtered signal in dB (the reference time is 0.5 s) (Avgf_T1)
3. Energy Equivalent Continuous Sound Level (Leq_T1)

```
% p_0 = 20e-6;  % N/m2

p_ref_S1 = rms(Orig_1f.S1);
Leq_S1 = 20 * log10(p_ref_S1 / p_0);

p_ref_S2 = rms(Orig_2f.S2);
Leq_S2 = 20 * log10(p_ref_S2 / p_0);

p_ref_S3 = rms(Orig_3f.S3);
Leq_S3 = 20 * log10(p_ref_S3 / p_0);
```

Print the output

```
vp.a = [Maxf_S1;Maxf_S2;Maxf_S3];
vp.b = [Avgf_S1;Avgf_S2;Avgf_S3];
vp.c = [Leq_S1;Leq_S2;Leq_S3];
```

```
save('Mic-AXF.txt','-struct','vp','-ascii')
```