

Analysis of preferred weight configuration for barebow shooting style

Proc IMechE Part P:
J Sports Engineering and Technology
2025, Vol. 239(3) 498–510

© IMechE 2023



Article reuse guidelines:

sagepub.com/journals-permissions

DOI: 10.1177/17543371231155510

journals.sagepub.com/home/pip



Francesco Pietra¹, 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 button⁷ (Figure 1). The *X* axis follows

School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, Johannesburg, Gauteng, South Africa

Corresponding author:

Francesco Pietra, School of Mechanical, Industrial and Aeronautical Engineering, University of the Witwatersrand, 1 Jan Smuts, Braamfontein, Johannesburg, Gauteng 2001, South Africa.

Email: Francesco.Pietra@wits.ac.za

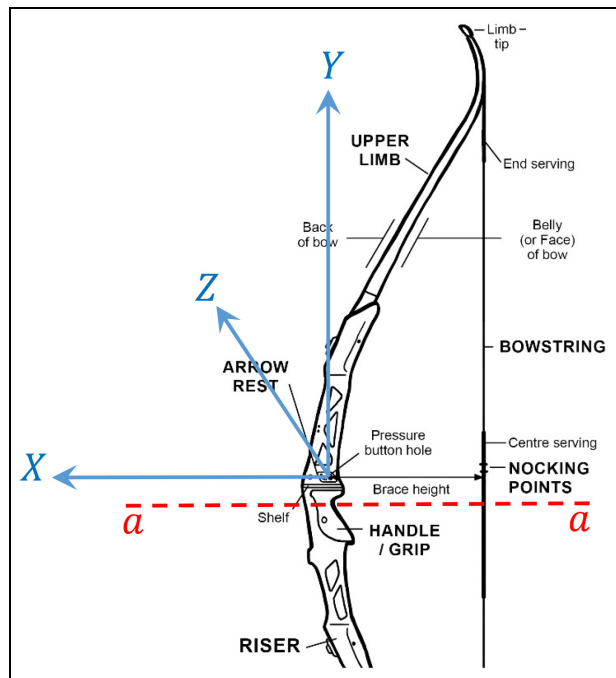


Figure 1. Global coordinate system.⁸

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).

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 4 in (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 7/3/2022¹). 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

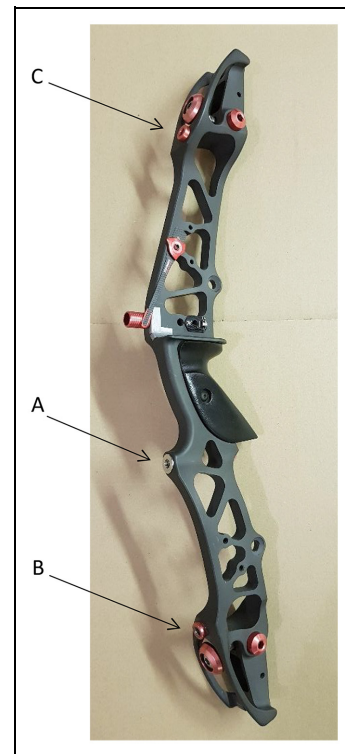


Figure 2. Riser Gray AIX. A, B and C are the attachment points.

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.

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

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

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.

Experimental set-up

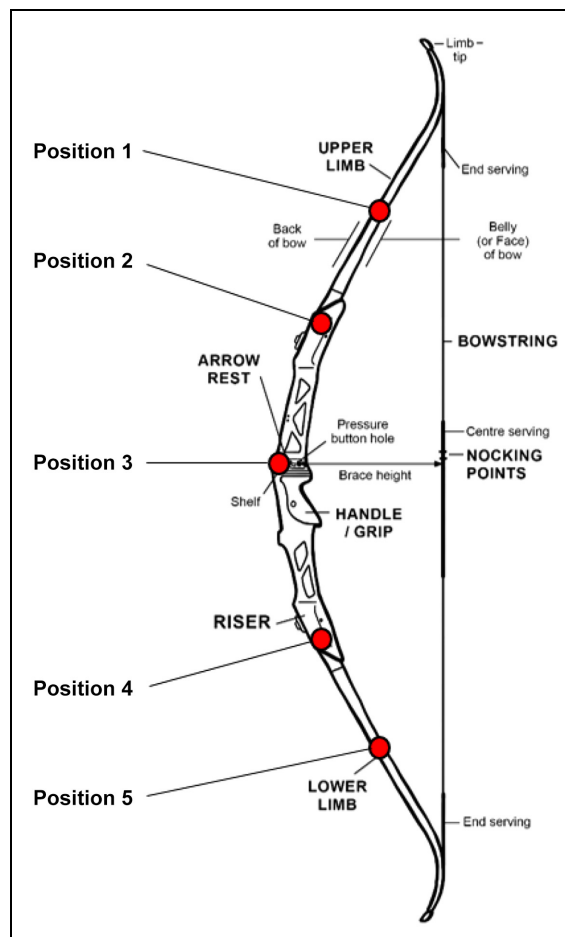
The riser used in the experiments was the Gray AIX 2019,¹⁰ which is considered within the South African barebow community, to be one of the best risers for this style.¹¹ The limbs were the Win&Win Limbs Wiawis NS Wood (long version, 32lb nominal poundage).¹² The weights were the Gas Pro Barebow Weights, with nominal weights of 350, 250 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 Kaminski.¹⁵ The 11 weight configurations tested are listed in Table 1.

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 guidelines¹⁶). The archers were asked to evaluate the proposed 11 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

**Figure 3.** Positioning of the accelerometer on the bow.

- 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

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]

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.

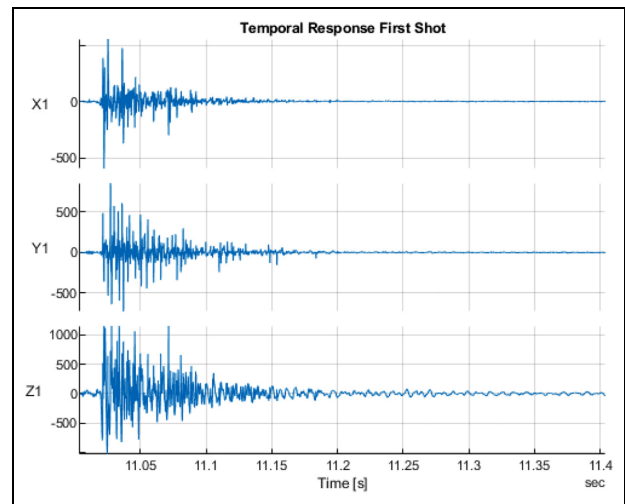
Objective metric: Vibrations

The vibrations associated with the shooting phase were recorded using a triaxial accelerometer from PCB Piezotronics¹⁷ 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).

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

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

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 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 4000 Hz. Given the complexity of the signal, an analysis based on a statistical approach was adopted. The following signal statistics were calculated²¹: 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.

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

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
	<i>r</i>	−0.412	0.550	−0.547	−0.480	−0.087	0.469	−0.625	−0.180	−0.628
	<i>v</i> [%]	17.0	30.3	29.9	23.0	0.8	22.0	39.1	3.3	39.4

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).

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 variables²² or, in other words, it gives an idea of the percentage of data points close to the line formed by the regression equation.

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,^{23–27} 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 4 to 8, 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.

The data analysis shows a good correlation between the filtered signal metrics and the perceived vibrations for Positions 2–5, 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

Table 4. 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	19,667	14,443	7728	25,595
200–0	1	1352.90	1176.50	477.06	1855.29	103.53	76.20	27.44	131.45	24,457	17,024	6215	30,440
250–0	2	1320.90	1224.34	473.68	1862.30	108.90	83.92	28.93	140.50	27,046	20,388	6755	34,537
350–0	2	1263.10	1193.36	455.44	1796.37	102.43	80.52	30.73	133.86	22,366	18,113	7730	29,801
200–350	3	1269.73	1122.05	770.75	1861.52	100.82	73.52	37.21	130.21	20,956	15,544	7383	27,116
250–350	3	1230.40	1155.39	511.49	1763.64	92.37	71.23	27.50	119.84	16,509	13,691	5900	22,244
200–250	4	1292.92	1103.69	696.13	1836.95	100.03	71.98	51.55	133.59	19,420	14,445	8017	25,496
350–250	4	1233.73	1165.71	524.19	1776.44	100.42	76.10	28.69	129.22	22,217	16,522	6458	28,430
250–200	5	1233.77	1150.80	691.47	1823.37	96.07	74.79	35.43	126.80	18,787	15,416	8321	25,687
350–200	5	1248.33	1165.86	523.87	1786.61	94.55	72.43	27.84	122.31	19,460	15,052	6305	25,397
V-Bar	5	1205.30	1160.20	371.84	1713.79	110.24	82.66	25.36	140.10	29,282	20,445	5553	36,142
	<i>r</i>	−0.824	−0.297	0.220	−0.575	−0.125	−0.009	0.129	−0.035	−0.079	−0.044	−0.099	−0.071
	<i>v</i> [%]	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 5. 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
	<i>r</i>	−0.657	−0.720	−0.471	−0.732	−0.605	−0.787	−0.611	−0.676	−0.505	−0.757	−0.558	−0.619
	<i>v</i> [%]	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 6. 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
	<i>r</i>	−0.680	0.337	−0.866	−0.895	−0.643	0.195	−0.860	−0.899	−0.817	−0.022	−0.684	−0.841
	<i>v</i> [%]	46.2	11.4	75.1	80.2	41.4	3.8	74.0	80.8	66.8	0.0	46.8	70.6

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.

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).

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

Table 7. 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
	<i>r</i>	−0.446	−0.447	0.505	−0.037	−0.560	−0.746	0.096	−0.690	−0.681	−0.742	−0.343	−0.705
	<i>v</i> [%]	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 8. 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	22,914	11,967	7638	26,955
200–0	1	1599.55	813.44	385.30	1835.40	110.29	55.41	27.54	126.46	25,053	12,406	5688	28,529
250–0	2	1562.12	909.88	432.52	1858.81	102.85	58.72	28.47	121.81	20,594	12,075	5985	24,612
350–0	2	1507.70	982.06	476.47	1861.35	104.11	63.27	29.63	125.38	21,859	13,352	6691	26,474
200–350	3	1296.82	729.60	384.12	1536.75	95.27	52.72	27.38	112.28	15,517	8992	6488	19,071
250–350	3	1311.71	832.30	358.37	1594.28	96.65	57.28	24.65	115.02	15,878	10,273	6053	19,856
200–250	4	1417.25	701.28	316.94	1612.71	100.51	49.75	22.14	114.32	17,008	8636	5520	19,858
350–250	4	1190.78	1059.15	376.96	1637.63	94.44	72.09	29.29	122.36	17,727	13,823	7189	23,601
250–200	5	1378.22	812.89	357.33	1639.50	95.17	54.78	22.49	112.09	15,997	9719	5478	19,503
350–200	5	1227.47	1015.92	455.85	1657.28	88.91	63.62	24.34	112.01	14,800	11,136	5153	19,225
V-Bar	5	1251.47	1197.41	388.67	1775.11	93.84	68.03	27.76	119.19	21,347	14,542	5978	26,512
	<i>r</i>	−0.719	0.422	−0.322	−0.388	−0.900	0.285	−0.644	−0.752	−0.694	−0.132	−0.489	−0.608
	<i>v</i> [%]	51.7	17.8	10.4	15.1	81.0	8.1	41.4	56.5	48.2	1.7	23.9	36.9

metrics. The results are shown in Table 9. 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).

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.

Subjective metric: Precision

The scoring of 30 arrows per weight configuration is shown in Table 10. The target was a WA – 122 cm, 10–

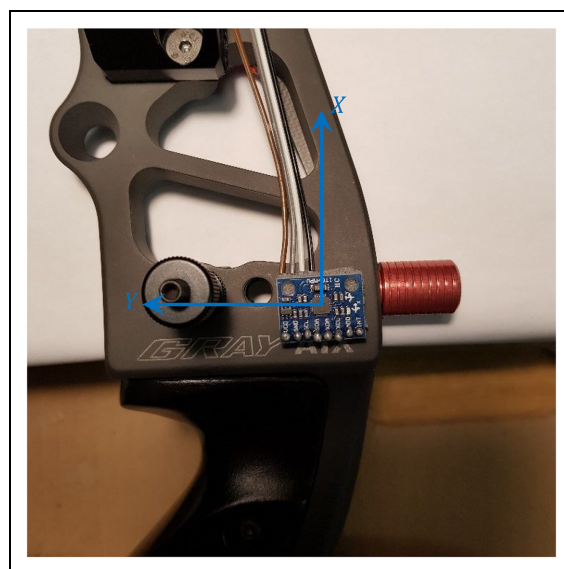


Figure 5. Arduino MPU6050 sensor and the local coordinate system.

ring target (maximum score 300 points), positioned 50 m away. The archer was from the Archers of the Zoo Lake Club (Advanced archer¹⁶). Columns 3 and 4 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

Table 9. 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.

Config.	Quality	Delta X [mm]		Delta Y [mm]		Delta Z [mm]		Delta Roll [°]		Delta Pitch [°]		Delta Yaw [°]		Avg. Displ. [mm]	Avg. Rot. [°]
		Abs. Avg.	Avg.	Abs. Avg.	Avg.	Abs. Avg.	Avg.	Abs. Avg.	Avg.	Abs. Avg.	Avg.	Abs. Avg.	Avg.		
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
	<i>r</i>	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
	<i>v</i> [%]	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

Table 10. 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

average of the three subjective metrics; weight balance, vibrations and dynamic behaviour, refer to Appendix A) has been added for reference.

Although this is a standard methodology to compare bow settings or, in this study, weight configurations,^{28–30} it has been demonstrated that the differences in score reported in Table 10 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 11 weight configurations, Park's theoretical approach³¹ 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 programme 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 10, 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 programme 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 (900–1050 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 Park³² 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.

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.

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.

Acknowledgements

The authors would like to acknowledge all the people involved in this study: Prof. Claudia Polese, for believing (sometimes) in this project. All the technical staff in the Workshop in the North West Engineering Building, University of the Witwatersrand, for the help and the work. A special thanks to the staff of the Archers of the Zoo Lake Club, Johannesburg, for the access to their facilities and to all the archers from the Archers of the Zoo Lake Club, for the hours spent testing the equipment.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

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.

ORCID iD

Francesco Pietra  <https://orcid.org/0000-0001-6447-7199>

Data

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

References

- World Archery Federation. World Archery, <https://worldarchery.sport/about-us> (2014–2021, accessed 13 June 2022).
- World Archery Federation. Sport equipment, <https://worldarchery.sport/sport/equipment> (2014–2022, accessed 10 August 2022).
- Archery Guidance. The Differences Between A Recurve And Barebow, <https://archeryguidance.com/recurve-and-barebow-differences/> (2022, accessed 13 June 2022).
- Ellison S. Choosing and using stabilisation, http://www.sthelensarchers.co.uk/documents/choosing_stabs.pdf (1996, accessed 13 June 2022).
- Frangilli V and Frangilli M. *The heretic archer*. Rome, Italy: Press Up S.r.l, 2013.
- Elliot M. *Reference guide for recurve archers*. Falkirk, 2002.
- Greenwood Osterley Archers. Olympic recurve bow setup, <http://www.tap46home.plus.com/mechanics/Recurve%20Bow%20Set%20Up.pdf> (2010, accessed 13 June 2022).
- Emmett J. Archery beginners recurve diagrams, <https://www.jessica-emmett.com/blog/archery-beginners-recurve-diagrams/> (2016, accessed 13 June 2022).
- Ellison S. Controlling bow behaviour with stabilisers, <http://www.wvac.asn.au/docs/StabilisersEllison.pdf> (1996, accessed 13 June 2022).
- Gray Archery. Gray Archery, <https://www.gray-archery.com/> (2021, accessed 13 June 2022).
- Archery Talks. Forum: Gray AIX riser - Any feedback?, <https://www.archerytalk.com/threads/gray-aix-riser-any-feedback.5293399/> (2017, accessed 13 June 2022).
- WIN&WIN CO.,LTD. Wiawis limbs, <http://www.wiawis.com/us/archery-limbs-list> (2022, accessed 13 June 2022).
- Gas Pro. Gas Pro barebow weight, <https://www.gaspro-vanes.com/category/acc01/everything-else> (2022, accessed 13 June 2022).
- Charles D. *Archery skills. Tactics. Techniques*. Ramsbury, Marlborough, Wiltshire: The Crowood Press Ltd, 2015.
- Kaminski J. *Tuning for performance: a comprehensive Olympic recurve archery tuning guide*. 2020. Independently published, USA.
- McHendry D. Sentient Archery, <https://sentientarchery.com/trainingprogrammes> (2021, accessed 13 June 2022).
- PCB Piezotronics. ACCELEROMETER ICP®, TRIAXIAL, Model 356A01, <https://www.pcb.com/products?m=356a01> (2022, accessed 24 December 2022).
- Test Dynamics. N19234, <http://testdynamics.co.za/ProductPage.php?id=N19234> (2022, accessed 24 December 2022).
- Kooi BW. Design and materials in archery. *Mater Sports Equip* 2007; 2: 248–270.
- Leach MR. Archery, arrow & arrow flight: recurve bow tuning, <https://www.meta-synthesis.com/archery/archery.html> (2005–2021, accessed 13 June 2022).
- University of Michigan. EECS 206 laboratory manual, https://www.eecs.umich.edu/courses/eecs206/public/lab/lab_all_student.pdf (2003, accessed 13 June 2022).
- Witte RS and Witte JS. *Statistics*. 11th ed. San Francisco, CA: Wiley, 2017.
- Söresson A. *Energy absorption and transmission in the hand and arm during high frequency vibration and impact*. PhD Thesis, Luleå University of Technology, Luleå, 1998.
- Adewusi S, Thomas M, Vu M, et al. Natural Frequencies of the human hand-arm system using finite element method and experimental modal analysis. *ResearchGate* 2014; CIRI-CMVA14-48: 402–417. <https://www.researchgate.net/publication/283546707> January 2014
- Oey H and Mellert V. Vibration thresholds and equal vibration levels at the human fingertip and palm. *ResearchGate* 2004. <https://www.researchgate.net/publication/228505903> January 2004
- Adewusi S, Thomas M, Vu VH, et al. Modal parameters of the human hand-arm using finite element and operational modal analysis. *Mech Ind* 2014; 15: 541–549.
- Dong RG, Wu JZ, Xu XS, et al. A review of hand-arm vibration studies conducted by US NIOSH since 2000. *Vibrations* 2021; 4: 482–528.
- World Archery. World Archery coach's manual: Level 2, https://issuu.com/worldarchery/docs/coaching_manual_level2 (2017, accessed 2 November 2022).
- McKinney R. *The simple art of winning*. Tokyo: Leo Planning Inc, 1996. pp.156–158.
- Easton. Arrow tuning and maintenance guide, <http://eastonarchery.com/wp-content/uploads/2019/08/TuningGuideEaston.pdf> (1999, accessed 2 November 2022).
- Park JL. Modelling archers' scores at different distances to quantify score loss due to equipment selection and technique errors. *Proc IMechE, Part P: J Sports Engineering and Technology* 2014; 228(4): 250–258.
- Park JL. Using group sizes to optimise archery equipment. *Proc IMechE, Part P: J Sports Engineering and Technology* 2021; 1–8. DOI: 10.1177/17543371211053716

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			Vibrations		
Weight configuration	Results	Evaluation	Weight configuration	Results	Evaluation
Naked	2.6	3.0	Naked	1.4	1.0
200–0	2.6	3.0	200–0	1.4	1.0
200–250	3.7	4.0	200–250	3.6	4.0
200–350	3.9	4.0	200–350	2.9	3.0
250–0	2.9	3.0	250–0	1.7	2.0
250–200	3.7	4.0	250–200	4.6	5.0
250–350	3.1	3.0	250–350	3.3	3.0
350–0	3.3	3.0	350–0	2.3	2.0
350–200	3.6	4.0	350–200	4.6	5.0
350–250	3.1	3.0	350–250	4.1	4.0
V-Bar	4.0	4.0	V-Bar	4.6	5.0
Dynamic Behaviour			Overall Quality		
Weight configuration	Results	Evaluation	Weight configuration	Results	Evaluation
Naked	1.7	2.0	Naked	1.9	2.0
200–0	2.0	2.0	200–0	2.0	2.0
200–250	3.4	3.0	200–250	3.6	4.0
200–350	3.6	4.0	200–350	3.4	3.0
250–0	2.3	2.0	250–0	2.3	2.0
250–200	3.6	4.0	250–200	4.0	4.0
250–350	3.7	4.0	250–350	3.4	3.0
350–0	2.9	3.0	350–0	2.8	3.0
350–200	3.9	4.0	350–200	4.0	4.0
350–250	3.9	4.0	350–250	3.7	4.0
V-Bar	4.1	4.0	V-Bar	4.2	4.0

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
	<i>r</i>	−0.412	0.550	−0.547	−0.480	−0.087	0.469	−0.625	−0.180	−0.628
	<i>v</i> [%]	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
	<i>r</i>	−0.546	−0.791	−0.437	−0.612	−0.411	−0.667	−0.536	−0.539	−0.683
	<i>v</i> [%]	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
	<i>r</i>	−0.559	−0.030	0.245	0.025	−0.349	0.162	−0.029	−0.152	−0.113
	<i>v</i> [%]	31.2	0.1	6.0	0.1	12.2	2.6	0.1	2.3	1.3

Position 4 – 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	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

(continued)

(continued)

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]
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

Position 5 – 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	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

Notation

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