

THE MEASUREMENT AND QUALITY OF HUMAN WHOLE BODY CENTRE OF MASS LOCATION DATA

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Declaration

I, Warrick McKinon declare that the work contained in this thesis is my own work, except to the extent indicated in the acknowledgements section. This thesis is submitted in the format, approved by the Faculty, of published work with accompanying introduction and conclusion.

Part of this work was previously submitted for examination as a Masters Degree and examined and approved but not awarded since the MSc was subsequently upgraded to the present PhD Thesis. This work has not otherwise been submitted for any other degree or examination in this or any other university.

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(signature of candidate)

19th Day of December, 2006.

Abstract

Since its first measurement in 1679, the usefulness of the location of whole body centre of mass (COM) data has progressed from having largely theoretical value into being an instrument with several diagnostic and applied scientific uses. This thesis describes first the biomechanical and measurement theory foundation of COM research and then details the historical development of methods to measure COM location and the various applied uses of this variable. Original research data presented in this thesis then go on to provide the first direct measurements of COM movement in walking humans. A second study quantifies the accuracy of the most commonly used current technique to quantify COM location (the kinematic segmental method) by determining the limits of agreement between it and a direct measurement method (the reaction-board), in lying and running subjects. In the latter studies a novel reaction-board measurement method is developed making use of life-sized projections of subjects in various stride positions and used to place runners into recumbent static running positions. These data demonstrate that reaction-board and segmental methods report COM locations with a mean difference of 1.6cm and agree to within limits of 6.0cm for the location of COM in recumbent individuals. The final study described in this thesis compares single COM measurements made using two kinematic segmental methods (models) to a direct suspension technique of measuring COM location. The suspension technique used is adapted from the original method of determining COM location upon which kinematic segmental methods derive their origin. The data show that both cadaver-derived kinematic models of COM, and kinematic models derived from live human data, differ from a direct COM suspension method, and that cadaver based estimates display greater accuracy (agreement with the direct suspension method). This study also uniquely provides information on the effect of whole body mass, body fat or body water on the accuracy of segmental models in male subjects.

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Table of Contents

Title page	i
Declaration	ii
Abstract	iii
Acknowledgements.....	iv
Table of Contents	vi
List of figures.....	x
List of tables.....	xv
Journal submissions and conference presentations emanating from the work presented in this thesis	xviii
Contributions of authors to each study.	xx

CHAPTER 1: Introduction to Biomechanics and to Measurement Uncertainty	1
1.1. Introduction to human biomechanics	2
1.1.1. Kinematics.....	3
1.1.1.1. The nature of human movement	4
1.1.1.2. Kinematic tools	4
1.1.2. Kinetics.....	6
1.1.2.1. The use of force platforms for the estimation of whole body centre of mass displacement estimation	8
1.1.3. Human Statics.....	10
1.1.3.1. The physical nature of the static state (equilibrium).....	11

1.1.4. Interpretation of biomechanical data	12
1.2. Introduction to measurement theory	13
1.2.1. The need for dependable measurements	13
1.2.2. Assessment of measurement quality (including measurement uncertainty)	15
1.2.2.1. Classical approaches to measurement uncertainty	16
1.2.2.2. Modern (International Standards Organization based) approaches to measurement uncertainty	18
1.2.2.3. Approaches to measurement uncertainty used in this thesis	21
1.3. References from chapter 1	25
 CHAPTER 2: The Measurement of the Human Centre of Mass Location in Ambulating Persons; a Review of its Legacy and Application. Rationale for the studies presented in this thesis.	28
2.1. Linking Notes.....	29
2.2. Review Article.....	31
2.3. Rationale for the studies contributing to this thesis	69
2.3.1. Aims of the research	74
 CHAPTER 3: Direct Measurement of the Centre of Mass Location in Walking Persons	75
3.1. Linking Notes.....	76
3.2. Original Paper	79

CHAPTER 4: The Agreement between Reaction-Board Measurements and Kinematic Estimation of Adult Male Human Whole Body Centre of Mass Location during Running.	92
4.1. Linking Notes.....	93
4.2. Original Paper	96
 CHAPTER 5: Adult Male Human Whole Body Centre of Mass Location Measurement: Magnitude of Differences between Segmental Kinematic Estimations and Direct Suspension Measurements.	113
5.1. Linking Notes.....	114
5.2. Original Paper	117
 Chapter 6: Conclusions, Limitations and Future Research	149
6.1. Conclusions.....	150
6.2. Potential limitations of this research	154
6.3. Further research.....	156
 Appendices.....	159
Appendix 1. Published definitions of both centre of mass and / or gravity.....	160
Appendix 2.1 Algorithm for marker tracking GUI based utility	163
Appendix 2.2 Algorithm for three dimensional reconstructions of marker locations from image based coordinates.....	174
Appendix 2.3 Algorithm for joint centre determination from marker locations....	174

Appendix 3.1. A copy of the internet web page showing the status of the review paper entitled: “The measurement of the human centre of mass location in ambulating persons; a review of its legacy and application”(chapter 2).	200
Appendix 3.2. A copy of the internet web page showing the status of the paper entitled “Adult male human whole body centre of mass location measurement: magnitude of differences between segmental kinematic estimations and direct suspension measurements” (chapter 5).....	201

List of figures

CHAPTER 2

Figure 1. Busts of Aristotle (a) and Archimedes (b), likely to be the two first authors of recording the physical phenomenon of the centre of mass. The construction of these and earlier statues also demonstrate how knowledge of the centre of mass of statues (or at least its implications) must have been known by sculptors, who predate these authors..... 38

Figure 2. The balancing board of Borelli (Table 10 de Motu Animalium, 1679). 44

Figure 3. A portrait of G.A. Borelli..... 45

Figure 4. The "apparatus for reporting forward and backward components of the pressure of the foot against the ground" (Fenn 1930). 46

Figure 5. The [reaction-board] apparatus of Reynolds and Lovett (1909). 48

Figure 6. The first diagram showing the segmental model of COM determination (Braune and Fischer 1889)..... 51

CHAPTER 3

Figure 1. Photographs showing the experimental procedure as seen from above.

Photograph a) shows a subject beginning to align himself to his pre-recorded image. b) Shows the same subject minutes later, aligned to his own image

(having been aided by two observers).....	83
Figure 2. Vertical centre of mass oscillation of one walking stride in two subjects with differing stature using the reaction-board method. The subject indicated by (+) was our tallest subject (stature 185cm). The subject indicated by (×) was our shortest subject (stature 170cm).	85
Figure 3. Scatter plot showing the lack of a relationship between measurements of subject stature and the vertical COM oscillation over one walking stride in six subjects.....	87
Figure 4. Scatter plot showing the lack of a relationship between measurements of subject stature and the horizontal COM oscillation over one walking stride in six subjects.....	88
Figure 5. Scatter plot showing the significant relationship between measurements of subject stature and the median COM height above the treadmill over one walking stride in six subjects.....	89
 CHAPTER 4	
Figure 1. Basic schematic diagram of the reaction-board system.....	99
Figure 2. The body positions adopted by subjects in experiment 1, as seen from above on the reaction-board apparatus.	101

Figure 3. Centre of mass oscillation in the vertical plane of one subject over one stride as measured using the reaction-board (closed dots) and the segmental (open dots) techniques.	104
Figure 4. Agreement between the reaction-board and the segmental techniques of measuring the median vertical height of COM over a single running stride using a Bland-Altman plot.	105
Figure 5. Agreement between the reaction-board and the segmental techniques of measuring the vertical COM oscillation over a single running stride using a Bland-Altman plot.	105
Figure 6. Schematic diagram of an individual running on a treadmill as seen from behind.....	111
Figure 7. Schematic diagram of a subject lying on the reaction board.	111
Figure 8. Construction of a triangle to derive the correction factor (CE).....	111

CHAPTER 5

Figure 1. Schematic diagram of the suspension device for whole body centre of mass location determination.	122
--	-----

Figure 2. A subject sitting in the suspension apparatus.....123

Figure 3. A graphical representation of a 3D model of one subject. Circles indicate marker positions, (including points A and B of the suspension apparatus, which define the suspension axis, represented by a broken line). The cross indicates the segmental estimation of whole body COM in this subject.124

Figure 4. The distance between kinematic COM location (Dempster model) and the direct suspension axis for a single subject over 12 seconds of data collection..129

Figure 5. The distance between kinematic COM location (Zatsiorsky/De Leva model) and the suspension axis for the same subject shown in figure 4 over the same 12 second data collection period.130

Figure 6. The relationship between mean distance between segmental kinematic COM location estimates and the suspension axis for each subject (an approximation of the error of COM location estimation) and adiposity (body fat percentage). Relationships are shown for both De Leva/Zatsiorsky (a) and Dempster (b)models. No significant relationship was found for either model ($R^2 < 0.15$).....131

Figure 7. The relationship between mean distance between segmental kinematic COM location estimates and suspension axis for each subject (an approximation of the error of COM location estimation) and body mass. Relationships are shown for both De Leva/Zatsiorsky (a) and Dempster (b)models. No significant

relationship was found for either model ($R^2 < 0.005$).132

Figure 8. The relationship between mean distance between segmental kinematic COM location estimates and suspension axis for each subject (an approximation of the error of COM location estimation) and percentage body water. No significant relationship was found ($R^2 < 0.001$). Relationships are shown for both De Leva/Zatsiorsky (a) and Dempster (b) models. No significant relationship was found for either model ($R^2 < 0.001$).133

List of tables

CHAPTER 3

Table 1. COM oscillation.....	84
--------------------------------------	----

CHAPTER 4

Table 1. Differences and limits of agreement between median COM locations and COM movements of the reaction-board and segmental methods in 4 lying positions.	104
---	-----

Table 2. Distribution of COM location derived variables from single running strides on 12 subjects.	105
--	-----

Table 3. Differences and limits of agreement between COM derived variables as measured on a reaction-board and using the segmental method of COM location determination on single running strides in 12 subjects.....	106
--	-----

Table 4. Limits of agreement and values of median two-point oscillation of COM in the horizontal and vertical running planes over six strides (n=6).	106
---	-----

Table 5. The limits within which the accuracy of the segmental method is defined.	107
--	-----

CHAPTER 5

Table 1. Segmental inertial parameters used in this study.....	126
---	-----

Preface and Description of Thesis Sections

The centre of mass (COM) of the human body is a physical manifestation of the entire human body and is the point relating to the body that requires the most energy to move from one point to another (when changing the body's inertial properties). The measurement of the location of the COM of a person is often (but not exclusively) carried out in the clinical and applied sports domains. Few studies however, have tested the accuracy (magnitude of variation between measurement and “true” values) of the measurement of COM location or displacement, in particular against direct methods' measurements.

The general aim of this thesis is to (1) introduce the field of COM biomechanics to readers; (2) review current and legacy COM theory and applications; (3) devise methods for the direct measurement of COM location and displacement and (4) use the latter direct measurement techniques to quantify the magnitude of error inherent to the (currently) most commonly used COM location measurement technique, the kinematic segmental method.

This thesis is therefore divided into six chapters. Chapter 1 introduces the fields of biomechanics and measurement theory (uncertainty), while chapter 2 reviews the legacy and current application of COM theory both in general and specifically in relation to the human body, and describes and compares methods that have been used to measure human COM location. Chapter 2 contains the first of four chapters in this thesis, which has been either submitted or published in manuscript form in a peer reviewed scientific journal. Importantly, the final section of chapter 2 describes the rationale for the empirical studies conducted in this thesis' chapters 3 through 6.

Chapter 3 contains the first data based study of the thesis, which provides direct measurements of COM oscillation in walking adult male subjects and is the second thesis chapter containing a paper which originates from a journal article.

Chapter 4 describes the agreement between the novel reaction-board technique and the more commonly used kinematic segmental estimate approach for COM location determination. The accuracy of the modified reaction-board quantified in this study allows several aspects of the accuracy of the segmental technique to be quantified in two dimensions when applied to both recumbent and running subjects.

Chapter 5 describes the agreement between a benchmark standard direct measurement suspension technique and two segmental estimate approaches for COM location determination that include three dimensional data. The suspension technique used in this study is akin to the methods used to originally validate the segmental methods. The suspension method has the greatest theoretical accuracy of any COM location determination technique in use today. The resulting comparison between the segmental and suspension methods is one of the most meaningful in quantifying the true error the modern day segmental kinematic method. Both chapters 4 and 5 are based on published or submitted journal articles.

In chapter 6, the experimental results presented in this thesis are summarized, their contribution to the field of COM location measurement is explained and the limitations of this research outlined. Note that references are described at the end of each chapter in which they appear and thus an all-inclusive reference list at the end of the thesis is not considered necessary.

**Journal submissions and conference presentations emanating from the work
presented in this thesis**

Submitted manuscripts

- **Warrick McKinon**, Craig G. Hartford, Christopher L. Vaughan, Daniel Joubert and Geoff G. Rogers. The measurement of the human centre of mass location in ambulating persons; a review of its legacy and application. Under review by the journal: *Gait and Posture*.
- **Warrick McKinon**, Craig G. Hartford and Geoff G. Rogers. Adult male human whole body centre of mass location measurement: magnitude of differences between segmental kinematic estimations and direct suspension measurements. Under review by the journal: *Journal of Biomechanics*.

Published Papers

- **McKinon W.**, Hartford C., Di Zio L., van Schalkwyk J., Veliotes D., Hofmeyr A. and Rogers G. (2004) The agreement between reaction-board measurements and kinematic estimation of adult male human whole body centre of mass location during running. *Physiological Measurement* 25: 1339-1354.
- **McKinon W.**, Hartford C., and Rogers G. (2005) Direct measurement of the centre of mass location in walking persons. *South African Journal for Research in Sport, Physical Education and Recreation* 27: 57-69.

Conference Presentations

- “A reaction board method for measuring whole body centre of mass oscillation for entire strides in runners”. Poster presented at the Physiological Society of Southern Africa, Sun City, South Africa, September 2001. **Presented by: Warrick Mckinon;** Authors: McKinon W., Hartford C., Hofmeyr A. and Rogers G.
- “The agreement between kinematic estimation of the whole body centre of mass position during running and direct measurements made on a reaction-board”. Oral platform presentation to the Physiological Society of Southern Africa, Stellenbosch South Africa, September 2002. **Presented by: Warrick Mckinon;** Authors: McKinon W., Hartford C., Di Zio L., van Schalkwyk J., Veliotes D., Hofmeyr A. and Rogers G.

Contributions of authors to each study.

As part of the declaration of the author of this thesis, the contributions of each author of the papers that make up chapters 2, 3, 4 and 5, which are under review or have been published, are described below.

Chapter 2

Warrick McKinon, Craig G. Hartford, Christopher L. Vaughan, Daniel Joubert and Geoff G. Rogers. The measurement of the human centre of mass location in ambulating persons; a review of its legacy and application. Under review at the journal: *Gait and Posture*. (see appendix 3.1 for supporting documentation as to the status of this manuscript).

The review article which makes up the core of chapter 2 emanates from an extended version of the literature review that was used for my Masters dissertation. After that dissertation had been examined and passed it was decided between my supervisors (Craig G. Hartford and Geoff G. Rogers) and I, that I should write it up as a free standing Journal article. At that time we also enlisted input from Professor Christopher L. (Kit) Vaughan, for his broad exposure to the generalised biomechanical audience, and of Professor Daniel Joubert, a physicist, so that he might check the concepts contained in the manuscripts for physics based accuracy. In particular Professor Joubert was approached for assistance with the description of the centre of mass and the direct measurement methods of centre of mass location. All authors have reviewed drafts of this review paper before it was submitted for publication. Both the first and final draft of this manuscript are ultimately Warrick McKinon's responsibility.

Chapter 3

McKinon W., Hartford C., and Rogers G. (2005) Direct measurement of the centre of mass location in walking persons. *South African Journal for Research in Sport, Physical Education and Recreation* 27: 57-69.

All the experimental design, data collection and analysis, drafting of written work and other tasks for this paper were performed by me with the guidance of my supervisors. Construction of the reaction-board and manufacture of other tools used in this study are described below in a more appropriate place.

Chapter 4

McKinon W., Hartford C., Di Zio L., van Schalkwyk J., Veliotes D., Hofmeyr A. and Rogers G. (2004) The agreement between reaction-board measurements and kinematic estimation of adult male human whole body centre of mass location during running. *Physiological Measurement* 25: 1339-1354.

The idea for this study emanated from many discussions between my supervisors and me. At a late experimental design phase, we enlisted the help of Dr Johan van Schalkwyk, who came up with the idea of extending the data collection phase of this study to include the recumbent (non-running) body positions, and who contributed in other ways to study design and interpretation. With the exception of welding and load cell design and construction, all the manufacture and testing of equipment including

reaction-board construction, camera and projector mounting, laboratory modification, signal processing design and software programming were performed by me. Because the data collection phase of this study required two people aside from the subject, I enlisted the assistance of Mr. Luca Di Zio, who assisted me with data collection. Mr. Di Zio also added refinements to our original experimental design with special reference to subject handling and reading of drafts of the manuscript. Due to his training in Anatomy, the kinematic (marker tracking) analysis for this study was conducted by Dr. D. Veliotis, under my supervision. Dr. D. Veliotis also reviewed written drafts of the manuscript. The design and manufacture of the sensors use in this study (load cells) was performed by Mr. Andrew Hofmeyr, an engineer who also gave us advice on the physical accuracy of written drafts. Both the first and final draft of this paper were ultimately my responsibility.

Chapter 5

Warrick McKinnon, Craig G. Hartford and Geoff G. Rogers. Adult male human whole body centre of mass location measurement: magnitude of differences between segmental kinematic estimations and direct suspension measurements. Under review at the journal: *Journal of Biomechanics*. (see appendix 3.2 for supporting documentation as to the status of this manuscript).

All the experimental design, data collection and analysis, drafting of written work and other tasks for this paper were performed by me with the guidance of my supervisors. Design and construction of the suspension apparatus, camera system and other tools

used in this study were performed by me. Algorithms for the entire kinematic process were either written by myself, written with the aid of others or taken from freely available sources (please see chapter 5 and appendix 2 for details).

Chapter 1

Introduction to Biomechanics and to Measurement Uncertainty

1.1. Introduction to human biomechanics

“The word ‘biomechanics’ is derived from the Greek *bios* meaning life and *mekhaniki* meaning mechanics, so that biomechanics may be said to be the study of the mechanics of life forms” [153]. The discipline of mechanics, a division of physics, is defined as the study of motion and the related concepts of force and energy [66]. Today, mechanics is further subdivided into classical mechanics (concerned with objects that are larger than atoms and which move far slower than the speed of light), relativity (mechanics of objects moving at any speed, but with special relevance to high speeds) and quantum mechanics, which extends into the subatomic domain [132].

Biological life does not extend into the relativistic (very high speed) or sub-atomic realms. The physical principles that are applicable to life are therefore more typically concerned with classical mechanics as well as the non-mechanical disciplines of physics including thermodynamics and electromagnetics. Although biomechanical research often encroaches into the electromagnetic and thermodynamic fields, biomechanics is fundamentally the study of classical mechanics of biological organisms and systems [74].

In order to further categorize and refine the description of the field, biomechanics has been further subdivided into the study of movement itself (kinematics) and the study of forces and kinetic energy (kinetics) [15]. A third, special case, not covered but closely related to both kinematics and kinetics, is the study of objects at rest (still or more correctly, in equilibrium). The latter branch of biomechanics is referred to as statics [68]. Although not often acknowledged, the study of structural biomechanics

(most often the study of the physical structure of biological tissues, including the measurement of mechanical stress and strain) is also considered as an additional subdivision of biomechanics.

In the sections that follow, I briefly introduce the topics of kinetics, kinematics and statics as they relate to the human body. This is followed by a brief section on how such biomechanical measurements are useful in the wide variety of applied realms. In all of the above sections, I focus only on the topics relevant to this thesis. For the same reason, in the discussions that follow, structural biomechanics is not further discussed.

1.1.1. Kinematics

The movement of a human can be said to involve the change in location, position or posture of a human body part or whole body relative to some point in the environment [74]. Most often this movement is quantified in three dimensions as a change in location of a point or set of points (described as translational motion), a change in the angle between points in a rotational system (such as a joint), or the change in velocity or acceleration in both rotational and translational movements. As a result modern kinematic tools aim to achieve the ability to quantify human movement in six degrees of freedom (translational motion in all three dimensions and rotational motion in the same three dimensions), and to do so with the greatest possible resolution in the temporal domain (in some cases allowing for movement to be measured between time points less than a thousandth of a second apart).

1.1.1.1. The nature of human movement

Modern biomechanical measurements are made on human movements which vary from movements of the finger joints [138] to large scale whole body movement such as the pole vault [104]. Like all other objects, the human body may experience movement due to either its own state of inertia or external forces acting on the body (or part thereof). In addition to these factors however, motion in live organisms is also brought about through the action of controlled internal chemical reactions which result in the movement of molecules and ultimately the movement of body parts or the entire organism. Most often it is this latter type of motion, originating from muscular action which is the focus of human biomechanical study.

The movement which is initiated from skeletal muscle has its origins in the interactions of the proteins actin and myosin, today referred to as sliding filament theory, originally described independently by Andrew Huxley and Rolf Niedergerke [82] and Hugh Huxley and Jean Hanson [83]. Experiments on both the running and walking subjects in this thesis (chapters 3 and 4) owe their original movement to muscular action.

1.1.1.2. Kinematic tools

Although historically the focus of human kinematics was placed on simple measurement such as running stride frequency and stride length [51], today a wide variety of tools exist for the measurement of both translational and rotational movement of the human body or of its parts. Measurement of rotational motion for example may be measured using automated electrogoniometry [107], two dimensional

optical tracking analysis [153] (although the latter method should be used with great care due to limited capacity to describe motion through multiple degrees of freedom; 3 degrees of freedom at most), three dimensional optical tracking analysis; or other three dimensional approaches [for example acoustic methods [57], and electromagnetic approaches [131]]. The latter measurement methods (with the exclusion of goniometry) are also useful for determining translational motion, in so doing quantifying the displacement, velocity and acceleration of single body parts or even the whole body (e.g. the centre of mass, as is the focus of this thesis). Accelerometry can be used in addition to these methods but should be limited to acceleration measurements (the integration of accelometric data to velocity and displacement vectors encounters error that could lead to misleading conclusions).

Due to its popularity however today the biomechanics literature often describes the word kinematics synonymously with optically based three dimensional tracking and motion capture. Current optically based measurement systems have a temporal resolution which extends from slow speeds [e.g. 25 HZ which has been said to be appropriate for slow walking movements [150], or quasi-static measurements (as used in the current thesis)]; to a theoretical maximal recording frequency of 10 kHz [98].

Most often the biomechanical use of optical kinematic measurement systems is focused on the measurement of movement in one or a series of joints. Many approaches exist for estimating the locations of joints, and in particular the joint centres, which enable the estimation of axes of rotation, the borders of body segments and therefore the location of different body segments. Approaches to model joints usually make use of skin surface markers which conventionally are either used to

define a set of local joint coordinate reference planes and subsequent definition of joint centres [42, 152]; or make use of helical axis modeling to define a movement based model of the centre of rotation of a joint [151].

General advantages of the estimation of COM location using the kinematic method include the ability of this method to offer three dimensional localization of the COM, the ability of the kinematic method to make measurements in subjects in any body orientation and in any environment. Disadvantages of modern kinematic systems for COM location estimation, include their prohibitive price, susceptibility to error due to image aberration and their reliance on simplified modeling of the human body. In addition kinematic systems used for COM location determination require body markers to be placed upon a subject's skin, which itself may alter the natural movement of a subject. Moreover, despite their extensive use, surface (skin) based marker placement approaches however are often incorrectly placed leading to measurement error [45], and are not necessarily accurate in their representation of skeletal structures [23, 29, 30, 141]. Much effort is currently being focused on attempts to investigate the nature of such error, with the hope of eventual correction algorithms [29].

1.1.2. Kinetics

Classical Newtonian physics provides the mathematical context within which human movement kinetics exists. The study of human kinetics is therefore concerned with quantifying the forces which either cause movement or are produced as a result of human movement. In order to achieve this aim reliance is placed on Newton's laws of motion and gravitation, which are able to define the components of motion such as

mass, inertia, acceleration, gravitational acceleration, energy transfer and collision theory. The Newtonian principles also allow for the consequences of human motion to be elucidated, both in context of human interactions with objects and independent of his/her environment, which uses many of the same tools.

The knowledge gained from kinetic analysis enable movements and their consequences to be well categorized and understood, the consequences of movement to be modeled, and interventions to be studied. Such knowledge may be useful in altering an undesirable outcome (such as in the kinetic study of gait pathology) or reinforcing a favorable trait (such as it the case where kinetics are used to train champion athletes).

Movement may be initiated for a number of reasons which have been characterized into two main categories, namely internal and external forces [154]. External forces are those forces which originate from outside the body, such as gravity or an externally applied contact force, whereas internal forces are those forces which act between body parts within the body [154].

Although the focus of this thesis is kinematic analysis of human motion, the ultimate implication for the studies contained herein may have implications for the energetic, force modeling, balance and inertial aspects of human biomechanics. All of these latter variables are ultimately kinetic in nature.

Because the focus of this thesis is not kinetics per se, an in-depth review of the tools used for kinetic study is not necessary. The only significant reference to kinetic tool

usage that occurs in this thesis is the reference to the use of force platforms to estimate the movement of the whole body COM. For this reason, to the exclusion of descriptions of other kinetic tools, only the basic theory behind the use of force platforms in the estimation of whole body COM movement is explained. The introduction to force platform measurements below is meant to compliment further description of force platform measurements provided in chapters 2 and 4.

1.1.2.1. The use of force platforms for the estimation of whole body centre of mass displacement estimation

A force platform (also sometimes referred to as a force plate) is a device capable of measuring the force magnitude and direction applied to its surface. Modern force platforms are able to measure the forces applied to the force platform surface in all three dimensions, a feat achieved through having different force sensors in each of the three dimensional axes. The force sensors used to make such measurements are usually either strain gauge based or piezoelectric in nature. The above description is essentially the first step in understanding how force platforms are able to estimate COM movement. For the next step of the explanation we will need to describe aspects of human locomotion.

When walking or running a human comes into contact with the ground, and in so doing propels him/herself in the direction of locomotion and in opposition to gravity. One consequence of this action is that the net force of action between the moving human and his environment during ambulation can be said to be between him/herself and the ground (assuming other external influences such as wind are negligible). A consequence of Newton's first law of motion is that the forces exerted by the human

onto the ground, are equal to those from the ground onto the human (assuming no significant system 'loss of energy' to deformation of either the ground or human; and other possible sources of energy transfer such as energy transfer to heat energy are negligible). These latter forces (from ground to human), are referred to in the biomechanists field as 'ground reaction forces'.

When a force platform is embedded in the ground, preferably in such a way as to be flush with the ground surface surrounding the platform [74], the force platform is able to measure all ground reaction forces between the ground and the ambulating human. If the mass of the human is known, Newton's second law of motion is able to define the acceleration of the human whilst in contact with the force platform (note that this assumes that, at the time of measurement, the human is only in contact with the force platform, i.e. no other body part is in contact with the ground). The acceleration that is defined through Newtonian principles, is the acceleration of the whole body COM, which can be integrated to calculate the velocity and then ultimately the displacement of the COM of the human subject. Note that the latter integration process requires the determination and/or estimation of integration constant including the initial velocity and initial location of the whole body COM. As is described in chapters 2 and 4, multiple methods have been used to estimate these constants.

Advantages of using force platforms for COM displacement measurement include their relatively simple installation (in comparison with a multiple camera segmental systems), their ability to take measurements at very high sampling frequencies (1000 samples per second or more) and the ability of force platforms to yield near instantaneous COM movement data. Force platform measurement of COM movement

also has the advantage of not requiring any marker placement or the placement of any other interfering device, to the body of a subject. Unfortunately however, force platforms do display their own unique difficulties. Although force platforms are able to measure COM displacement relative to a point in space, the location of that point is not discernable using this method, actual COM location determination is therefore not possible. Another difficulty associated with force platform measurements is that, as explained above, this method requires a double integration analytical step. Double integration carries with it an inherent problem, where any signal error is propagated over time, leading to possible magnification of error as readings are made. Lastly, being reliant on either strain gauge or piezoelectric technology, force platforms are susceptible to various sources of error, including electrical drift, temperature related oscillation and electrical hysteresis

1.1.3. **Human Statics**

In the preceding section we have seen that multiple approaches exist for the measurement of human motion. It is sometimes useful however to be able to describe the location of the human body and its parts as well as the forces acting on the body, when no movement occurs. To achieve this, the study of human statics uses the same tools described in the kinematic and kinetic sections above. Because of its use of established kinematic and kinetic tools, and probably due to its lesser usefulness in biomechanical applications, few texts distinguish the study of human statics from the kinematic and kinetic subfields of human dynamics. For the purpose of this thesis however, where much of the data collected was performed under static conditions, I have found it necessary to describe some concepts unique to human statics, as they apply to the measurements made in the studies of this thesis. Actual description of

how statics is applied to the measurement of COM is described in chapter 2 where it is more appropriate.

1.1.3.1. The physical nature of the static state (equilibrium)

The observation of movement of an object relies on an observer being in a different state of motion to the moving object. Relative to a theoretical observer on a far away planet for example, every object on the surface of the earth could be said to be moving at a remarkable speed (due at least to the speed of rotation of the earth, rotation of the earth around the sun, and so on). Relative to one another however, two observers inside an isolated system on the surface of the earth could be said to be in a state of no movement (at rest).

Due to the physical environment on the earth's surface being subject to gravitational influences, a state of rest can only be achieved through opposition forces acting to counteract other forces such as gravity. A person lying on the ground may for example be in a state of rest if the forces acting on his/her body from the ground exactly counteract the influences of gravity. It could therefore be said that the static state can only be achieved on the earth's surface when the forces acting on that body are exactly counteracted by opposing forces, such that the net force acting on the body is equal to zero. The latter point may also be described as: a static state is achievable when an object is in a state of force equilibrium. Of course it should be noted that it may be theoretically possible for there to be some part of the universe where all forces acting on an object would be negligible, allowing for a static state to exist without the need for equilibrium of forces.

1.1.4. Interpretation of biomechanical data

In the sections above many of the approaches and measurement tools available to biomechanists have been described. These methods have lead to a detailed understanding of human body movement and enabled the description of such movements in mathematical language. Unlike other sciences however, the usefulness of biomechanical data is not chiefly concerned with purely biomechanical knowledge development. Instead biomechanical data often finds its greatest usefulness in other biological realms where interpretation of the biomechanically generated data is made in relation to the context of that field. A similar circumstance is true for the science of analytical chemistry, a pure science in its own right. Although analytical chemistry is a pure science, it is seen as vital for clinical diagnosis, food and other product development, as well as a great variety of other applications. Like analytical chemistry the field of biomechanics is most useful when the data it generates is used in other biological contexts.

Examples of the applications of biomechanics in other biological fields include: the description of anatomical structures under moving conditions; the theoretical evolution of phenotypic traits of animals (with description of how different morphologies may have contributed to evolutionary survival); the identification of traits which contribute to sporting performance; the clinical diagnosis of movement disorders; the physiological understanding of movement and the effects of pharmacological drugs on movement. Arguably the most recent application of kinematics in particular has been its use in entertainment where virtual environments are created and characters are modeled either for video games or movie characters.

1.2. Introduction to measurement theory

Although the content of this thesis is squarely placed in the field of biomechanics (as introduced in the previous section) and specifically in the domain of COM biomechanics (as introduced hereafter in chapter 2), the tools employed in the studies described (particularly chapters 2, 4 and 5) are derived from another field of science, namely metrology. Metrology is defined by the International Standards Organization (ISO) as the “field of knowledge dealing with measurement” [85]. As such the field of metrology includes: the study of definitions of accepted units of measurement, the study of the quality and characterization of measurements and instruments, the establishment of traceable chains documenting the accuracy of measurements and the applications of all the above in all other realms but most particularly the legal realm [2, 81].

The wide scope of metrology makes a generalized review of the field a misguided undertaking for the current thesis, because only a few metrological tools and concepts are directly relevant to the studies described in this thesis. The sections below are therefore refined to include a general introduction to metrology, a description of tools used to assess the quality of measurements as well as an introduction to approaches that are used to compare measurement techniques.

1.2.1. The need for dependable measurements

The description of, and comparison between any of the quantities use by man in everyday life is dependant on the existence of reliable measurement. Economies rely on commodities that are traded according to weight, length or a multitude of other

measures. Clinically, measurements are needed in order for diagnoses to be made, appropriate treatment interventions to be conducted and for signs and symptoms of quality, efficacy and safety to be monitored. Aircraft and all other modes of transport rely on measurement of a wide range of variables, not only for their navigation and carriage capabilities, but for every aspect of their design and construction. Similar arguments, detailing the need for measured quantities could be applied to almost all human endeavors.

All empirical scientific endeavors require (by definition) measurement. Scientific measurements allow for hypotheses to be tested and therefore knowledge to be gained, refined and evaluated. Measurement, as a result, is one of the very cornerstones of science.

Despite the importance of measurement a single measurement without context is seldom useful. To be useful the additional concept of context in which measurements are made within the framework of other measurements is needed. Most often measurements need to be compared, which can occur in a variety of ways. It may for example be important to be able to compare different measurements over time, in different locations and environments, and to do so using different measurement devices, is also often important. Standardization of measurements is therefore important. The quality of measurements (a topic arising from standardization) is discussed below.

For a more detailed account of the philosophical and historical development of measurement theory please consult the following references: [22, 97, 139, 140]. Note

that due to the nature of philosophical papers being different from (differently structured than) scientific articles (where facts can be quoted from original articles), the latter references have not been specifically cited in the text above.

1.2.2. Assessment of measurement quality (including measurement uncertainty)

No measurement available to humans is absolutely accurate [66]. There are many ways in which a measurement may vary from the true value. Although as is described later, many techniques exist to describe the differences between true values and measurement estimates of these true values, following from international conventions, current paradigms collectively refer to the measurement and approximation of these differences as measurement uncertainty [85]. The sections below deal with methods that are used to quantify and categorize different types of measurement uncertainty. Once again, as in other sections, only those topics with relevance to this thesis are discussed.

Worthy of mention but not further discussion is that, at the subatomic level (where measurement theory is taken to its minuscule extreme), there are further complications to measurement uncertainty, namely “Heisenberg’s uncertainty principle”. The reason for including this point here is that many physics and metrological texts refer to measurement uncertainty purely in the context of this principle. However as we will see below, such considerations are not generally appropriate to human biomechanics.

In 1927, Werner Heisenberg described his “uncertainty principle” for which he received the Nobel Prize for physics in 1932. Heisenberg’s principle is concerned with the measurement of the movement of a single particle and defines the natural limits within which an observer can measure the motion of that particle [78]. At the spatial scale at which human biomechanics operates however, the influence of Heisenberg’s uncertainty principle on an object the size of a hand for example would only account for a measurement uncertainty of 10^{-34}m [66] and can therefore be neglected.

1.1.2.1. Classical approaches to measurement uncertainty

In a classical metrological approach the difference between a measured value and a true value is referred to as measurement error [53]. True values in turn are classically estimated through the identification of a “preferred procedure” [46], which is defined by “agreement among experts” [54]. As we will see later however, more recent approaches to metrology and measurement uncertainty accept the concept that a true value is never known [89], and is, from the perspective of the experimenter always theoretical [84].

Making use of the classical assumption that an estimated true measurement is able to be identified, it is possible to estimate the error of measurement through comparison with true value estimates. The resulting error of measurement can broadly be classified into two categories, namely (1) random and (2) systematic measurement error [53]. Differences between these two types of error exist in that random error is randomly distributed around the true value, whilst systematic error favors one direction away from the true value (in any number of dimensions). Associated with

the concepts of random and systematic error is the concept of measurement bias. Measurement bias may be defined as the difference between a true value and the average of measurements made over all possible repetitions of the process [11].

Once both error and bias are known it becomes possible to define two more classical metrological concepts, namely accuracy and precision. Accuracy of a single measurement is the “closeness of agreement” between a measurement and a true value [53, 84]. Accuracy involves a combination of random error and bias components [53, 84]. Unlike accuracy however, measurement precision is defined as the “closeness of agreement” between independent measurements [84]. Note that the latter definition does not relate to a ‘true value’ [53], a principle which accounts for the possibility that a set of measurements may be inaccurate (due to bias), but at the same time remain precise (display only small differences between measurements).

The two remaining principles of classical metrology that have relevance to the studies contained in this thesis are the concepts of repeatability and reproducibility. To understand these concepts and the differences between them, it must first be made clear that measurements may be repeated under different sets of circumstances. In circumstances where conditions are identical, occur in the same laboratory / environment and are conducted by the same operators, a measurement of repeatability may be assessed between measurements [5]. Repeatability is therefore a type of measurement precision under such conditions. Reproducibility is assessed when the precision of measurement is assessed in measurements obtained by identical test items in different laboratories (with environments copied) and with different operators [5].

1.1.2.2. Modern (International Standards Organization based)

approaches to measurement uncertainty

Although classical metrological terminology and approaches are still used extensively, in the early 1990s the International Organization for Standardization (ISO) and all of its affiliate international metrological bodies presented a revised approach to measurement uncertainty [85]. One of the major reasons for doing so was the realization that although the classical approaches acknowledge that a true value is not perfectly quantifiable, they do not account for the consequences of this knowledge. Since the classical approach would require a known “true” value prior to the assessment of measurement error in a new measurement, and that “true values” themselves have inherent (unknown) error, a circular argument exists when trying to benchmark the error of a subsequent measurement [89]. The revised approach has attempted to correct this failing and was also able to formalize definitions for measurement uncertainty across disciplines, incorporate a number of principles previously unaccounted for and eliminate a number of redundancies inherent to the classical approach [60, 89].

The 1993 publication of the ISO Guide to the Expression of Uncertainty in Measurement (popularly referred to as the GUM) introduced the first documentation of a “consensus view” on how measurement theory should be calculated and expressed [90]. One of the departures from classical concepts is that the term and concept of “measurement error” is far less emphasized, mainly due to the observation that ‘true values’ cannot be exactly quantified [144]. Instead the principle of a standard measurement, which is acknowledged as being an “imperfect reflection of

the ‘true value’ ” [60], is used to conduct a far more thorough analysis of uncertainty as described hereafter.

The term measurand, introduced by GUM differs from the more classical ‘measurement’ in that all measurands are reported with an accompanying measure of precision (usually a standard deviation). In some fields of measurement however a numerical measurand may not be best suited to the description of the quantity being described. In such cases both the measurand and its variation are quantified in some other more appropriate manner (as may occur for example in the study of behavior).

Once both the measurand and standard (agreed but imperfect) value have been described the quantification of measurement uncertainty becomes possible. The GUM approach involves a number of sequential steps which I will loosely describe next. First it is recognized that each measurand is achieved through a series of ‘measurements’, but is reliant on a more complex measurement system [136]. In most modern day biological or engineering measurements, measurement systems may include multiple components (including for example a set of similar or dissimilar sensors, all of which have some level of interaction, conversion and signal amplification steps and an ultimate recoding phase which reports a value). This latter series of system components is referred to as a traceability chain.

The next step of the GUM based measurement uncertainty determination is that each of these steps is described mathematically in relation to the ultimate measurand [89]. Hereafter each identified step in the traceability chain is required to be further scrutinized, and have its own measurement uncertainty defined mathematically in one

of two ways. Type A measurement uncertainty determination is applied when multiple measurements of the particular step of the traceability chain can be made (or obtained from prior measurements/reports) thereby allowing for a standard deviation assessment of that step to be made. Type A measurement uncertainty determination is thereby able to define measurement uncertainty of many of the steps in the traceability chain, contributing to an ultimate measurand. Type B measurement uncertainty determination is applied to steps in the traceability chain where statistical procedures are not possible; and some other informed estimate needs to be made (and this assumption stated).

The result of the above GUM based measurement uncertainty determination steps is that a modeled mathematical description of all the parts in the traceability chain can be made. Such a model may also include other variables such as correction factors. The ultimate analysis of the constructed model is performed next where sources of uncertainty are identified, compared and the propagation of uncertainty from step to step is identified. Many mathematical approaches may be used to make such analyses including correlation methods [136]. The ultimate uncertainty of the entire system (including all smaller steps and overall uncertainty) is described and recorded.

The modern GUM approach to metrology has certain advantages over classical approaches. In particular, the GUM approach does acknowledge the imperfections of standard measurements (ultimately true to all measurements: see Heisenberg's uncertainty principle above for example). The modern approach also requires a formal dissection of the measurement system such that the measurement of uncertainty of each part in the traceability chain is identified and the propagation of uncertainty is

investigated. This is in contrast to the classical approach where more of a “black box” approach is employed in which chance accuracy of a system could arise in situations where opposing uncertainties may cancel one another out inside the measurement system and never be identified. Furthermore, the more transparent GUM approach establishes a basis for further debate and testing of assumptions ultimately leading to a more complete understanding of the measurement uncertainty of a system including the propagation of uncertainty along the traceability chain.

1.1.2.3. Approaches to measurement uncertainty used in this thesis

While the most recent approaches to measurement theory (section 1.2.2.2. above) have clear advantages over the classical approach, particularly in respect of standardization of terminology and the thoroughness by which measurement uncertainty is quantified, no studies have applied these principles to the field of whole body COM biomechanics. The studies described in chapters 4 and 5 both assess the measurement uncertainty of the most popular COM location measurement approach, namely the kinematic segmental method.

The traceability chain for the kinematic segmental approach is a complex and multifaceted system. To illustrate this, I will briefly describe the input and output variables into and resulting from the measurement system, as well as some of the traceability chain steps needed to estimate human COM location using an optical tracking kinematic based method.

The input data and variables used by a kinematic segmental measurement system may include: image footage (containing pictures of body markers or calibration points); known locations of calibration points (known physical dimensions of a standardized object, usually either a ‘wand’ or a ‘calibration frame’); the known locations of cameras; a set of segment inertial parameters (appropriate for the subject under study, used to model the human body); the mass of the subjects and certain other pre-measured characteristics of the subject; as well as an algorithm that is able to estimate joint centres from marker coordinates. I will assume that the single output variable for this measurement system is a three dimensional COM location relative to some known point in space.

Some of the main steps in the traceability chain are:

- Image capture and processing.
- Marker tracking (identification of the location of body markers within images).
- Three dimensional marker location reconstruction (construction of a virtual model).
- Joint centre location estimation from marker coordinates.
- Application of segmental inertial parameters and measured characteristics of the subject to the three dimensional model (derived from recumbent data on other humans or cadavers).
- COM location estimation.

In order to conduct the studies described in this thesis, it was important to adopt an approach that was both consistent with modern (GUM based) principles, but also to

do so in a way which was not contradictory with the more familiar conventional ‘classical’ methodology. To do this, we firstly identified areas of the traceability chain inherent to the kinematic segmental method, which may be assessed for measurement uncertainty. We did so, focusing on kinematic segmental approaches either used in published studies which apply COM data or those approaches described in biomechanics textbooks. Since many of the current steps in the traceability chain are currently receiving individual attention (such as the modeling of joint centres using various marker based approaches, the comparison of computerized tracking algorithms, or the use of different marker properties and types), we decided to either evaluate other aspects of the traceability chain, or to reassess traceability chain steps using novel approaches; and to look at the measurement uncertainty of the measurement system as a whole.

The following bulleted points made up the main aspects of the kinematic segmental method traceability chain and measurement system that were investigated in this thesis:

- The overall measurement uncertainty when comparing kinematic methods to a two dimensional reaction-board standard (chapter 4).
- The effects of upright COM data being reliant on recumbent segment inertial parameter measurements (chapter 4).
- The repeatability of COM measurements (chapter 4).

- The segment inertial properties used to model the whole body COM comparing different approaches –cadaver derived and live human derived data (chapter 5).
- The overall measurement uncertainty when comparing kinematic methods to a three dimensional suspension standard (chapter 5).

Notice that the nomenclature of these sections has remained consistent with the more conventional and easily understood ‘classical’ methods, which are (currently) more suitable to a biomechanical and general scientific audience.

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Chapter 2

Literature Review:

The Measurement of the Human Centre of Mass Location in Ambulating Persons; a Review of its Legacy and Application.

2.1. Linking Notes

In the preceding chapter the context of biomechanics and measurement theory was introduced. Chapter 2 specifically introduces the theme of the current thesis, namely centre of mass (COM) biomechanics, defines the concept of the human COM, places it in context of the biomechanical and applied fields where COM measurements have their application, and details the historical progression of attempts to describe and measure the location of the human COM.

Section 2.2 is also a free standing review manuscript which, at the time of this thesis submission, is under review at the journal *Gait and Posture*. Part of section 2.2 (the review article subsection 2) refers to the existence of many different definitions of the human whole body COM within the biomechanical literature. Due to word number constraints imposed by the journal *Gait and Posture*, examples of such definitions could not be placed into the text of the review paper. Therefore these are included in the appendices as Appendix 1. Quotes are shown as the definitions of the COM as they appear in different texts sourced from the literature. For the purposes of this thesis figures and their captions have been placed in the appropriate places within the text of the article.

Section 2.3 describes the rationale for the studies conducted in this thesis. The rationale has been placed here after the reader has read chapter 1 and chapter 2's sections 2.1 and 2.2. As a result the reader has been introduced to the background of COM biomechanics and is familiar with all the necessary subtleties of the field into which the questions are posed and is therefore equipped to consider the rationale of the subsequent thesis sections where the experimental chapters are found.

2.2. Review Article:

The measurement of the human centre of mass location in ambulating persons; a review of its legacy and application.

The measurement of the human centre of mass location in ambulating persons; a review of its legacy and application.

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Abstract

Giovanni Borelli (1679) first measured the location of the human centre of mass (COM), which he quantified as lying ‘between the buttocks and the pubis’ in a recumbent man. Since then many refinements to the techniques used to measure human COM have been made. Today COM location can be measured using methods that range from the tedious but accurate suspension method, to ‘near real time’ methods that make use of body segment based models (kinematics) or force integration (force platform) techniques. This paper reviews the development of COM location measurement methods, the data that such methods have yielded and outlines the known and newly emerging applications for COM movement data, with special reference to the validity of such data.

Abstract word count: 119 words

Key words: centre of mass, measurement, gait.

Introduction

The task of describing the position or movement of an object which occupies volume in three dimensions is not necessarily a simple task. One of the greatest steps in solving this problem was the discovery of the centre of mass (COM), a special point determined by the mass distribution of objects. Applied to the human body, the knowledge of COM location and movement has facilitated a great deal of progress in the understanding of human motion, balance, and the interaction between man and his environment.

Ambulation makes up between 3% and 27% of a Western human's awake activity [113]. A large proportion of the energy expended during ambulation is used to move the body's COM against gravity, to change its state of inertia, or to change the kinetic energy of the limbs with reference to the COM [25, 108]. Furthermore, the ability of a person to balance while stationary (maintain a constant vertical position within a base of support) or during movement is reliant on COM placement. Quantifying the movement of the COM is therefore useful to both the study of human energy expenditure and balance. Added to this is the need for COM data in the modeling of the human body for a multitude of applications such as the design of human operated machinery, prostheses or in the design of virtual computerized environments. The many uses of COM data have made these measurements an important quantity, with ever increasing application. In the light of few other attempts to do so, in this review we summarize the history of COM measurement theory and its applications.

1. Application of COM measurements

Knowledge of the location of the human body COM is considered essential to a variety of applications in the scientific, clinical and other applied realms. In purely scientific terms, COM data have been used to elucidate our understanding of a great variety of themes including biomechanical efficiency, balance, proprioception, gait and mechanical work [14, 26, 49, 80, 108, 126, 137].

Applied and clinical uses of COM data are also becoming more commonplace. In the clinical setting COM data have been used to evaluate age related changes in balance [72, 91], diagnose imbalance disorders [32, 73], identify gait pathologies [37, 48, 50, 71], describe falling [111] and evaluate the effect of limb amputation and corrective devices [67, 95, 142]. At present clinical uses of COM location data therefore include the evaluation of gait, falling risk, vestibular function as well as testing the efficacy of clinical devices and procedures.

Other emerging applications of COM data include equipment design and movement analysis. In particular, COM data have been used in the study of human movement in weightlessness [118] and the modelling of human movement [16, 112, 133]. Applied to the sporting realm, COM data have been used for the measurement of mechanical efficiency in athletes [7, 8, 127, 149] and the measurement of COM movement as a contributor to sport specific performance in a wide variety of sporting codes e.g. the hammer throw [38], high jump [39], hurdles [100], long jump [102], pole vault [104, 129] and triple jump [62].

In addition to specific human activities where COM data have obvious application, it is common for people today to perform a large portion of their daily activities in combination with machines. Often such man-machine combinations act as a single unit. The design of such machines (either those which carry or are carried by humans) have made use of COM measurement of machine and human separately, as well as that of both together. Two classical studies of the human COM arose from just such applications. Braune and Fischer [19] studied the influence of the Prussian Infantry's equipment on their COM, while Dempster [47] was interested in the COM of military machine operators. Another example where such COM studies have occurred includes the design of wheelchairs [96].

2. The emergence of the concept of the centre of mass of objects

At an appropriate age, human infants learn to place their COM within a base of support formed by their feet to enable them to stand or walk. This observation, and the observation of the need to balance the body in an infinite number of possible positions of stability, most likely dates to the time of the evolution of human cognition but due to its unrecorded nature, is lost in the mists of prehistory.

2.1. Legacy of COM concepts

From the design of ancient humanlike statues such as those created by the Egyptians, Greeks and other ancient cultures where a statue COM is placed above a specifically designed base of support, it is evident that knowledge of COM or at least the balance implications of such a point to the human body has been with us for a long time.

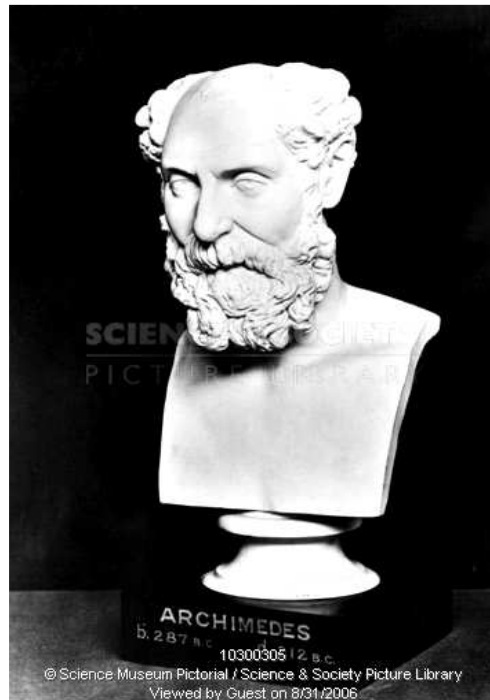
It is most likely that the first words recorded to describe the COM are those of Aristotle [9, 10]. Aristotle described the importance of the centres of objects both in his discourse on the heavens (*De Caelo*) as well as his writings on the movement of animals (*De Motu Animalium*). In many parts of his discourse about animal movement (*De Motu Animalium*), Aristotle refers to a far more tangible centre of motion concept, as a point of rest against which a limb or other body parts could be moved:

“...and the middle of the body must needs be in potency one but in action more than one; for the limbs are moved simultaneously from the original seat of movement, and when one is at rest the other is moved... Again, it is a reasonable arrangement that the movements arise in the centre upon movements in the parts, and in the parts upon movements in the centre, and so reach one another.”

(Chapters 9 and 11, *De Motu Animalium*[10]).



(a)



(b)

Figure 1. Busts of Aristotle (a) and Archimedes (b), likely to be the two first authors of recording the physical phenomenon of the centre of mass. The construction of these and earlier statues also demonstrate how knowledge of the centre of mass of statues (or at least its implications) must have been known by sculptors, who predate these authors.

Within 50 years of the death of Aristotle, the first reference to the COM of an object in a purely physical sense was made by Archimedes of Syracuse. Archimedes supplied both a definition for the COM (although this source document has been lost, but is referred to by Archimedes in other treatises [77]), and spoke of its properties. He related COM to the buoyancy of an object (in “*the water and other liquids*”) and to balancing a pair of objects, which are connected by a solid rod (in “*the equilibrium of planes*”, part 1).

Relatively little appears to have been added to the body of knowledge related to COM for the next 1500 years. The contributions that did come forth however were mainly related to the COM and astronomical position of the earth [36, 121].

The beginnings of modern empirical physics began with a number of noteworthy physicists of the late renaissance, all of whom demonstrated, with developing insight, the concept of the COM. The writings of Galileo Galilei [63] are of particular importance in that they develop both the idea of the COM and document the work that preceded it (*De motu antiquiora* written in 1592 but only published after Galileo's death [148]). Galileo confirms that up until the sixteenth century very little had been added to the ideas put forward by Archimedes (*De motu antiquiora*).

By the time of Newton much of what we understand today about the COM had already been described. Nonetheless the contributions of this researcher were significant. Newton put forward many different definitions for what we today describe as the COM. In a dynamic sense Newton referred to this centre of motion as being:

“a point which rests when a body is moved with any circular but not progressive motion” and “in every body there is a certain point called the centre of motion about which if the body be anyway circulated the endeavours of its parts every way from the centre are exactly counter poised by opposite endeavours” [109]

Newton's description of the "centre of motion" coincides with an object's COM since Newton uses the terms "centre of motion" and "centre of gravity" interchangeably [79].

Newton's *Principia* [109] also documents his physical laws (Newton I and II -from which kinetic extrapolations of COM data can be made; and Newton III upon which one of the methods of its measurement is now based- i.e. the force platform) as well as the universal law of gravitation (used today to calculate the potential energy of COM position and therefore work required to elevate the COM). Today we are aware that subsequent findings have demonstrated that the Newtonian theories are not applicable to the very small (atomic and sub atomic) realm or very fast moving (near light speed) circumstances. For the purposes of human based COM measurements, we can safely assume that Newtonian theories hold.

2.2. *Modern COM definition*

Today many complementary definitions for both the COM and centre of gravity exist in the biomechanical realm. For the purposes of this review paper we first define the COM of the human body as the imaginary point in or about the isolated human body at which the entire mass of the body can be considered to be concentrated. The COM is the point that can be used to describe the translational movement of the entire human body.

The manifestation of the COM of an object can be explained purely from the application of Newton's first and second laws of motion. Any collection of matter that can be said to be discernable as an isolated object can be described as made up of

smaller matter particles which are in some way held together by a combination of forces, mainly electrical or chemical in the supra nuclear realm. When a force is applied to the object, through force application to one or more of its smaller parts, the object may deform or fragment, or if the forces holding the object together are strong enough, the applied force will be transferred through the object from part to part. The net result of the applied force in the latter case will be to change the state of motion of each part in turn, in a manner dictated by the inertia of each part of the object, and the forces between parts. The resulting motion of the object as a whole is a combination of rotational and translational motion.

The translational motion, which is a mass weighted averaged translational motion of all the parts of the object, can be described by the motion of the COM. This motion is equivalent to the motion of a single point particle with mass equal to the total mass of the object and responds as if all the forces applied to the object are applied at the COM. The rotational motion of the object can be described as the motion of the parts of the object relative to the COM, in other words, as the motion of the object seen by an observer who is moving with the COM. The rotational motion is equivalent to the rotation caused by all the forces acting on the body about an imaginary axis that passes through the COM.

The COM is therefore a unique, mathematically defined concept that at any time is determined by the mass distribution of an object. The concept of the centre of gravity (sometimes used synonymously with COM) also depends on the mass distribution of a object, but in addition it depends on the universal law of gravity and the properties of the gravitational field in which that object is found. In a uniform gravitational field,

the location of the centre of gravity and the location of the COM coincide. In a non-uniform gravitational field, the two points do not coincide and in fact the centre of gravity is not a very useful concept. The lesser usefulness of the centre of gravity of an object in a non-uniform gravitational field arises because its location changes relative to the mass distribution depending on where in the non-uniform field the mass is found. Note that the gravitational field on the earth's surface is assumed to be approximately uniform especially when considering changes relative to the spatial scale over which a human body spans (approximately 2 meters) [6].

Despite the well understood physical and mathematical definitions of the centres of mass and gravity, the use of these concepts in a wide variety of research fields has regrettably resulted in varied definitions for both variables. As a result, even recently, the careless use of the terms centre of gravity and mass, has motivated authors to publish articles reminding researchers of the proper use of such terms [93].

3. Methods of measuring the location and degree of movement of the human

COM

Over the last 350 years various methods for measuring the location of the human COM have been devised by different researchers. Initially measurements were made either by balancing or suspending people or frozen cadavers. Later, less arduous but more indirect measurements on live humans were devised. Today automated measurement of COM location or displacement is a widespread and popularly measured variable in biomechanics laboratories. This section of the review, documents the evolution these methods.

3.1. *Direct means of measuring COM location*

Mass is the fundamental property of matter to resist a change in velocity [154]. By generating an applied force which exactly counters the movement of an object, that object is brought to rest (static equilibrium). When the above situation occurs on the earth's surface, the centre of gravity of the still object lies within a volume defined by two variables: a) the area of contact between the object's surface and the applied force and b) a vector which emanates from the earth's centre to the latter 'area of contact'. The application of the above 'applied force' can be positioned with varying precision, allowing the volume within which the centre of gravity of the object is localized to be refined. Through this method a two dimensional localization of the COM (perpendicular to the gravitational vector) becomes possible. The accuracy of such a COM measurement is dependent on the care taken to limit the applied reaction force to as small an application area as possible.

The two COM location measurement methods that make use of the direct physical localization of COM explained above (with no intermediate sensor or measurement system), are the balancing or suspension methods. All other methods used to determine COM location relative to a known point in space are derived (either directly or indirectly) from balancing or suspension techniques. The first two subsections below describe how balancing and suspension methods have been applied to measurement of the human body COM, while the remaining sections refer to measurement of COM displacement and location using other physics-based measurement methods.

3.1.1. Balancing

The earliest recorded method used to determine the location of the human COM was made using a simple board and pivot (Figure 2, Borelli 1679[17]). Borelli (figure 3) described locating the centre of “gravity” of a man “stretched out at length”, finding it to be located between the buttocks (“*Nates*”) and the pubis [18]. Borelli’s simply designed measurement technique had the advantage of being directly dependent on physical laws (potentially of high theoretical accuracy). Borelli’s measurements, however, suffered some degree of inherent error because he neglected to locate the COM of his board alone, or alternatively to balance his board and fix it in that balanced position prior to his subject lying on the board [19].

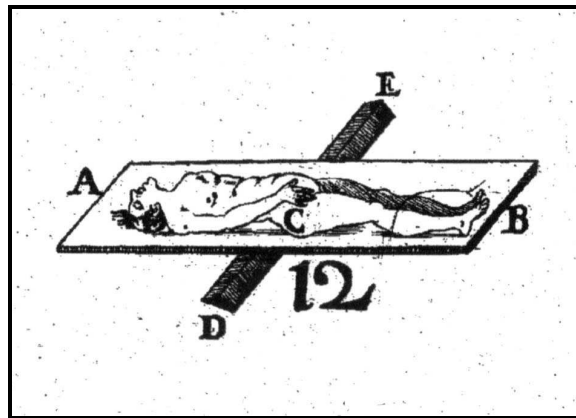


Figure 2. The balancing board of Borelli (Table 10 de Motu Animalium, 1679).

The Webber brothers [147] used equipment akin to that of Borelli [17] , but ensured that their board was pre-balanced. Webber and Webber [147] repeated the measurements of Borelli on a male cadaver and defined the location of the COM as lying 721,5mm from the crown and 947,7 mm from the heel [19]. In 1860 Harless

[75] repeated the cadaveric measurements of the Webber brothers as well as measuring the mass and COM locations of each body segment [33].



Figure 3. A portrait of G.A. Borelli

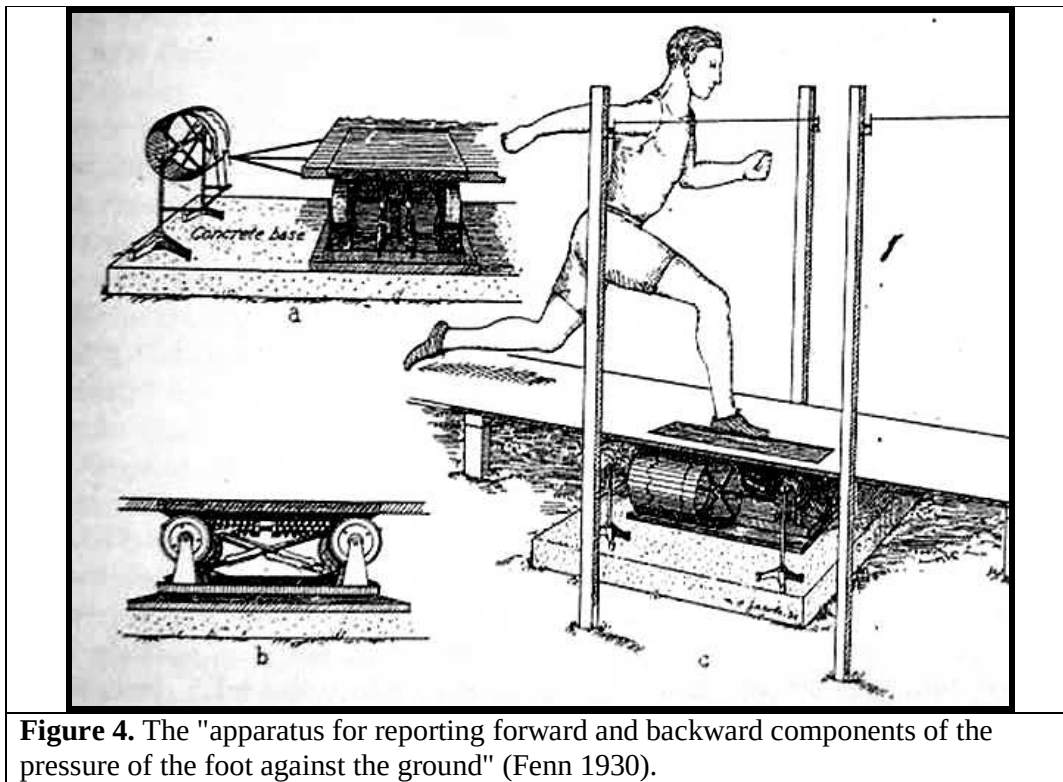
3.1.2. Suspension

Braune and Fischer [19] introduced the suspension method of measuring human cadaver COM. This method relied on a concept well known since the time of Galileo (1592), that the force applied at a single suspension point of an object that has come to rest, acts along the line that passes through the COM. Making use of pointed iron rods that were hammered (with the aid of a “blacksmith’s hammer”) into frozen whole cadavers as well as individual body segments to locate individual segment COMs, Braune and Fischer made use of the stable equilibrium offered by suspension in order to measure both whole body COM location and the way in which those locations changed when different body parts were removed from the cadaver. They

also used the same technique as a reference standard to compare their segmental technique with a direct measure of the COM

3.1.3. Force platforms

In the previous section it may be evident that direct measurement of the location of the COM, is a time consuming and arduous task. The same however, is not necessarily true for direct measurement of the displacement (the magnitude and direction of movement between two points of unknown location) of COM since measurements of ground reaction forces make it possible to double integrate body acceleration data in a far shorter time.



Three years after the publication of the work of Braune and Fischer, Etienne Jules Marey developed a “dynamographic platform” [59], which is recognized as the first functional force platform [27]. Such devices initially relied on mechanical tracings of the “pressure” that a runner uses to deform rubber bulbs [4] or metal springs [59] (Figure 4).

Even though ground reaction forces had been quantified for both walking [4] and running [4, 59], prior to World War II, these were not yet used to calculate the displacement of COM during ambulation [59]. The earliest reference to such a procedure is that of Elftman [55] who recognized that it was possible to double integrate ground reaction forces, and with the proper use of Newton’s second law of motion, obtain data of the displacement of COM if it was possible to conduct a “proper evaluation of integration constants” [24]. Since then, the use of force platforms to calculate the movement of the human COM has become widespread. These techniques have become more refined in recent times [134].

Like all ground reaction force methods, force platform measurements require estimation of two integration constants, which are conventionally estimated through an averaging technique or assumed to be zero [14], accurate measurement of the true mass of the subject as well as the gravitational acceleration constant at the site of measurement. The need for a high degree of accuracy in these initial measurements is that, through the process of double integration any small magnitude of error is summed throughout the duration of measurement. The accuracy with which force platform techniques are able to produce the actual integration constants is thought to influence the accuracy of the data obtained [70, 126].

3.1.4. Reaction-boards

In 1909 the first direct technique of COM location measurement that did not rely on either suspension or balancing was published by Reynolds and Lovett [124]. Their device (Figure 5), that would later be recognized as the first reaction-board [35, 68], was designed to measure the COM location of a standing subject.

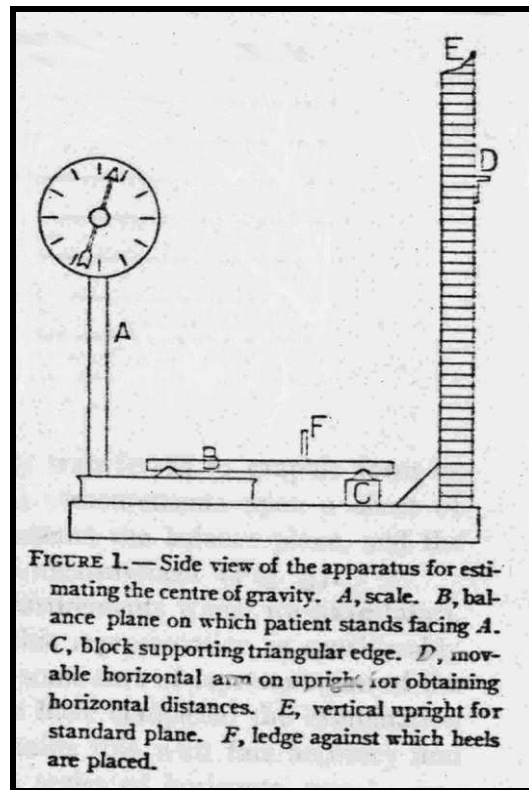


Figure 5. The [reaction-board] apparatus of Reynolds and Lovett (1909).

Since direct measurements of COM location are conducted when the whole body centre of pressure coincides with the centre of mass projection onto the board surface, direct measurement of the COM location has been typically limited to being made when a subject is not moving and therefore in a state of stable equilibrium. Direct

measurements of COM location when a subject is standing (or in any other “unstable” body position where energy is required to maintain a stationary position) may encounter error as the centre of pressure of the body moves about the base of support created by the feet [3, 14, 145]. To overcome this, researchers have laid subjects in recumbent positions in order to emulate less stable body positions.

Today reaction-boards remain in use primarily for either measuring the recumbent height of COM of subjects lying on the board surface, or for measuring changes in position of the COM in an individual who changes between two static body positions. Like the board of Reynolds and Lovett [124], reaction-boards of today measure the centre of pressure of objects placed on their surface, which in static subjects coincides with a two dimensional localization of the COM. Such measurements include the direct measurement of the COM in positions that emulate the long jump [102], diving [69, 122], the sprint start [116] and “normal”, “pike” and “stride” positions [41].

3.1.5. Other methods

Although balancing, suspension, force platform and reaction-board techniques are the four most widely used methods to directly measure either the location or displacement of COM, two other related methods have been developed. These less well-known methods are seldom used in practice today. The first of these was the “Wisconsin see-saw” which comprised a 10 ft (3.05m) long rigid bar balanced on a pivot. At one end of the bar, at a known distance from the pivot, a large iron weight with known mass was placed. At the other end of the bar the subject of known mass would lie in a supine position. Simple torque algebra is used to calculate the COM location of the stationary subject, usually marked with the use of a plumb line [43].

The second of these techniques that has been reported to measure the human COM location directly is the method of tipping-standing [43]. This technique was made popular in 1863 by von Meyer [19, 43] and involved a subject maintaining a rigid body position. Once subjects were as rigid as they could make themselves, they were slowly tilted in an anterior or posterior direction until they lost their balance. Markers were placed onto the legs of subjects which were filmed in the sagittal plane. Images containing leg markers at the points of both anterior and posterior falling, and which contained a horizontal horizon were used to calculate the position of the centre of mass (pressure) of the subject using trigonometry [43].

3.2. Indirect means of measuring COM

Direct measurement of the location of the COM (suspension, balancing, reaction-boards, the Wisconsin see-saw and tipping-standing) is an extremely time consuming activity, requiring meticulous attention to detail. Although this is not necessarily true for the direct measurement of the displacement of COM (which requires either the above methods or force platform techniques), alternative methods have evolved which are both time efficient and repeatable.

3.2.1. Cadaveric and other segmental model methods

In 1889 Braune and Fischer [19] adapted work of von Meyer [146] (who investigated the changing COM location upon removal of different body segments), to develop the segmental method of COM determination. Using their suspension technique and studying cadavers they measured the COM location of each cadaver and recorded the

anthropometry of each body. Next Braune and Fischer dismembered each cadaver and recorded the COM, dimensions and mass of each body segment. For one cadaver (cadaver 6) they constructed a drawn model relative to a set of arbitrary axes (three dimensional Cartesian volume) of the body, marking body dimensions and locations of each segment's COM (Figure 6).

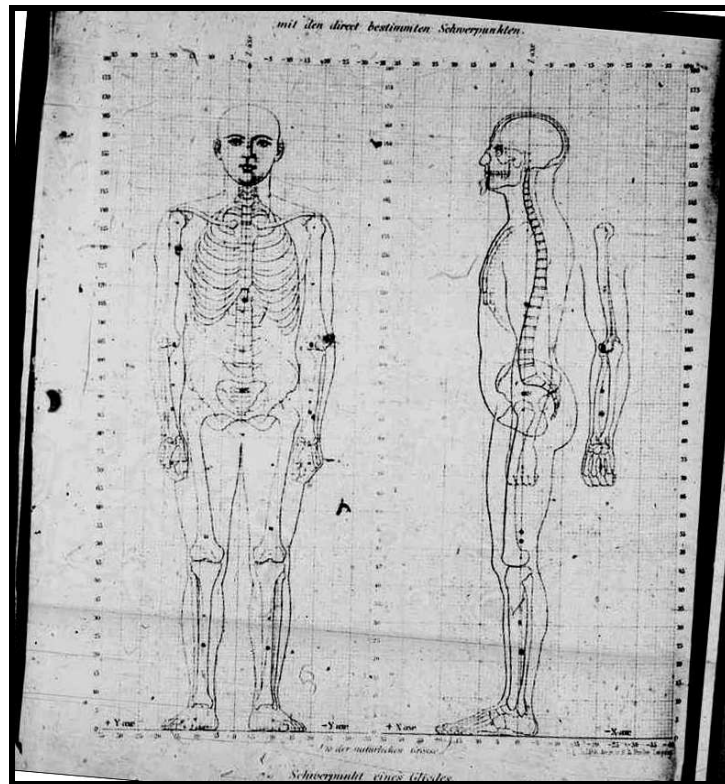


Figure 6. The first diagram showing the segmental model of COM determination (Braune and Fischer 1889)

This three dimensional model (Figure 6) was then investigated, one dimension in turn, in the following way: the position of each body segment (relative to the arbitrary axes) was quantified and assigned a mathematical weight (according to its mass). The resulting products of body segment positions and masses were averaged to yield a one dimensional COM location; this procedure which was then repeated for each

Cartesian axis resulted in a three dimensional estimation of the position of the COM of the subject.

Braune and Fischer found a 0.8cm concurrence between their segmental method and actual measurements of COM location, but derived this from only one standing body position (what they termed the ‘normal position’) and from one frozen cadaver.

Although high-speed cinematography had been in existence for the analysis of human movement since 1887 [106], Fenn [58] was the first to use the method of Braune and Fischer, and cadaver measurements of Fischer [61] to estimate changing locations of COM in running subjects. The use of cinematography in combination with the segmental method as used by Fenn [58] is today referred to as the kinematic method, which in this review is used synonymously with the segmental method. Even today however, for the most part, the segmental technique relies on banks of cadaveric segment inertial data. The development of suitable banks of information has grown to meet such needs. Some of the most noteworthy contributions in this regard include: Dempster [47], Clauser and colleagues [33] and Chandler and colleagues [31]. Plagenhoef and co-workers [119] have advocated the use of the centre of volume of limbs as these can be used to estimate the position of segment COMs without the need to resort to cadaveric data. This idea and similar approaches using gamma-ray scanning, have made it possible for researchers to report mean allometric segment inertial data based on far greater sample sizes than those of the cadaver-based studies ([119, 155]).

More recently studies have focused on conducting similar measurements on population groups whose anthropometry differs from the conventional studies. This has allowed for greater refinement of cadaveric derived models to subjects of diverse morphologies. In particular measurements have been made on older adults [87, 115], children [86], infants [130] and the different genders [87].

Nowadays methods that make it possible to use a subject's own body segment inertial data for analysis by the segmental method exist. Pioneering steps in this regard can be attributed to Brooks and Jacobs [20], Martin and colleagues [99], and Mungiole and Martin [105] who used gamma mass and MRI scanning to determine segment inertial properties. More recently similar approaches have been adapted to video based systems [128], Dual Energy X-ray Absorptiometry [52, 64] and reaction-board methods [114]. The evolution of the body segment inertial data has been more extensively reviewed elsewhere [117].

Today modifications on this same segmental principle have been refined enabling a myriad of biomechanical analyses to be conducted on running subjects. Perhaps the most important of these improvements is the ability for current technology to move from a two-dimensional analysis plane to a three-dimensional volume, which has been made possible by the advent of multi-camera image calibrations [1, 21]. Although not a focus of the current review, it should be remembered that the accuracy of image based techniques is partially dependent on the ability of markers to reflect the locations of centres of mass of limb segments. The continuous refinement of marker sets and models to estimate the location of joint centres is a process that will result in improved COM data quality.

Data from segmental kinematic analysis have been shown to be comparable to measurements of COM oscillation using techniques such as the force plate and sacral movement methods [13, 65, 70, 92]. In contrast however, “physiologically significant” differences were found between the segmental method and force platform data when measuring COM vertical oscillation during walking [126]. Additionally, Arampatzis *et al* [8] noted that kinematic data was not reliable for calculating mechanical power of running.

One possible reason for the difference between segmentally derived COM locations and more direct measurements may be that the fixed rigid segment data do not adequately estimate the properties of the body parts of a living subject, a concern that was raised about such measurements in the study that discovered the segmental technique:

“The question arises as to whether there can be any centre of gravity in the body at all because it is not a fixed mass but consists of separate limbs that always change in position in relation to each other and cannot even be considered masses in the mechanical sense and because fluids are always flowing through the body. In the absolute sense the answer is certainly no. Mosso (1884) has actually proved, with his balance, that the centre of gravity of the body is always changing due to respiration and circulation.”[19].

3.2.2. *Methods based on measurements of single markers*

A few studies have reported that COM displacement could be estimated by measuring the displacement of the sacrum [12, 88, 143]. These studies have separately demonstrated that measurements of sacral displacement are easily obtained with either the use of a multi-camera motion analysis system (observing only one rather than many moving points) or using a device known as the kinematic arm, respectively. Saini *et al* [126] showed that, in a group of 25 healthy female volunteers, there was no significant difference between segmental and sacral marker estimates of the vertical excursion of the COM during walking. For this reason and because the sacral marker is a far less onerous technique than the segmental method, Saini *et al* [126] recommended the use of the sacral markers as superior to that of the segmental method.

Although this method is undoubtedly the least time consuming and displays the greatest ease of use of all the COM location / displacement techniques, its accuracy must remain in doubt as no rigorous comparisons between sacrum location and direct measurements of COM locations have been made.

4. Comparisons between measurement methods

Today the most commonly used method to measure COM location is undoubtedly the segmental technique. This method has however unfortunately seldom been compared to direct measurements of COM location. The first of these studies was also the initial study to have compared measurements of COM locations using different techniques and is the study that discovered the segmental method [19]. Braune and Fischer compared their highly accurate suspension method to their segmental reconstruction

of a cadaver. Having referenced their measurements to a three dimensional Cartesian set of axes, they set the origin at the position of the COM (as determined by suspension) in both the anterior-posterior (x) axis, and mediolateral (y) axis. The origin of the longitudinal (z) axis was set at the heels. They were able to categorize the accuracy of their segmental reconstruction according to these three reference axes. In the x-y (transverse) plane Braune and Fischer found that their segmental calculation lay within 0.22cm of their direct measurement. Along the longitudinal axis their direct technique had found the COM to lie 93.3cm from the heels, as compared to 92.5cm for their calculation. They however only did this in one position (what they termed the “normal position”) and in one cadaver (cadaver IV).

To the authors’ knowledge only two other documented studies have compared the segmental method of COM location determination to that of a direct measurement method. Davis [41] compared reaction-board measurements to segmental method calculations on more than one subject and in more than one position (the positions he referred to as the “normal”, “pike” and “stride” positions). Davis found that the methods varied from between 1.9 and 3.5cm. Although Davis used only two subjects (each subject analyzed in all three positions), his segmental method was far more closely related to the methods used today to determine COM location than those of Braune and Fischer [19]. One last study, conducted by the authors of this review, found that the segmental and reaction-board methods agree in their methods of assessing vertical COM oscillation in multiple running strides to a magnitude of between 5.1 and 0.1cm [103].

Because direct methods of measuring COM location are both methodologically difficult and time consuming and for this reason seldom used in practice, measurement comparisons of COM location with balancing, suspension or reaction-board methods are rare. The two most commonly used methods to estimate the displacement of the COM of the human body are the force platform and segmental methods. For this reason, comparisons between these two popular methods have occurred most frequently. Benda *et al* [14] found that segmental and different force platform methods used to measure COM displacement (different ways in which integration constants are estimated) displayed greater agreement in standing rather than in walking individuals (mean square difference of 0.3 and 1.4 cm², respectively). Eng and Winter [56], showed that in slightly more complex movements (arm movement during standing) the segmental and force platform methods report similar but no identical COM moment (where force platform measurements begin to differ from segmental estimates at the end of a measurement period, which the authors attributed to “cumulative integration errors”). The latter study attributed such changes to the inability to exactly quantify integration constants for the ground reaction force methods.

Belli *et al* [12] investigated mechanical energy changes during ambulation using both segmental and force platform techniques. In addition they compared these data and the data collected through the use of their recently described third method, the kinematic arm. Belli and co-workers found that significant differences existed between the three techniques which they attributed to “an overestimation of the potential work computed with the kinetic arm” and “an underestimation of kinetic work computed with film analysis” (the segmental method).

Thirunarayan *et al* [143] also conducted comparisons between the segmental, force platform and sacral marker methods. In this study vertical oscillation of COM was shown to be similar when measured by sacral marker and segmental methods, both of which were significantly different to data from a force platform technique. In addition to the three methods compared by Thirunarayan *et al* [143], the same group conducted a similar study, which included a “reconstructed pelvis” COM estimate method [126]. Saini and her colleagues [126] found that “The forceplate method provides information that is statistically significantly different from the results of the kinematic methods. The magnitude of the difference is large enough to be physiologically significant and further studies to define the sources of the differences and the relative validity of the two approaches are warranted”. The magnitude of their differences ranged between 0.2 and 0.5 cm (difference between means of the subject group for each technique, since raw data was not presented).

Because COM data can be used to work out energetic quantities such as mechanical power, work and energy, comparisons between segmental and force platform data of these quantities have been performed. Arampatzis *et al* [8] found that differences between kinematic (segmental) and force platform derived data of these quantities as measured on a group of eight runners (running at different speeds) exist. Calculations of mechanical power based on force platform data were far more closely related to running speed than segmentally derived data (r^2 of 0.9 versus 0.48 respectively) leading Arampatzis *et al* to conclude that “kinematic data cannot be recommended to determine efficiency of movement”.

In 2004 Gard *et al* [65] compared force platform, segmental and sacral marker methods of estimating COM vertical oscillation in subjects walking at different speeds. These researchers have demonstrated that the sacral marker method tends to overestimate COM vertical oscillation (in relation to the other methods), with increasing magnitude as walking speed increases. In this study, force platform and segmental methods never differed significantly. Most recently Gutierrez-Farewik *et al* [70] have compared segmental and ground reaction force derived COM excursions. The latter study showed that the COM excursions can agree to root mean squared (RMS) error difference of better than 13mm, but that this accuracy is influenced by many factors including ground reaction force integration constant estimation and the degree to which segmental models are able to mirror the true physical characteristics of subjects.

The above studies generally show that differences exist between techniques that determine the degree of COM displacement in human ambulation. Force platform methods show the greatest degree of COM oscillation, whilst the segmental technique displays the lowest. This trend does however have exceptions [65, 143], the reasons for which remain to be determined.

5. Prospects

The use of COM data is becoming ever more popular as a tool for the assessment and modeling of human activities. Commonly, measurements of COM location are made in subject groups using the segmental method, whilst measurements of the degree of movement of COM are made using this method and force platform techniques.

The accuracy of these methods to estimate COM parameters is seldom verified with comparisons to more direct methods. Despite this, the accuracy of the segmental method in particular, is bound to continue improving through more robust modelling of a subject's segment inertial data and more accurate marker sets. The accuracy of the ground reaction force derived (force platform) methods is also sure to improve as efforts are made to improve the estimation of integration constants.

5.1. The importance of valid COM measurements

Despite the varied ways in which COM data are used today, the quality of such data is seldom reported. COM location data may be required to be accurate. For example, in the study of imbalance, falling is an “all or nothing” event. The degree of error (accuracy) with which the variables are measured directly relates to the specificity and sensitivity of the diagnosis of susceptibility to falling or to the categorization of movement pathologies. In addition, since ambulation is a cyclical event and many cycles are repeated over the time needed for a person to walk or run from one point to another, small errors in the measurement of variables specific to describing each ambulatory cycle may conceivably result in large errors of energy estimates over the entire movement period. It is therefore important to have an accurate measure of COM movement in the study of gait efficiency.

5.2. *The future*

The future of human COM location and displacement measurement, due to the fundamental physical nature of these variables, will doubtlessly continue for a long time. The multitude of possible ways in which this data may be used in the future is limited only by the ability of the human imagination to find new applications for modeling the human body. It is likely that the current trend to use segmental modeling of the COM is here to stay, and in the author's opinion this method displays the greatest utility. Aside from new applications of COM data, probable developments in the COM measurement field will no doubt include the quantification and reduction of the errors associated with the segmental method COM measurement.

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2.3. Rationale for the studies contributing to this thesis

Presently, the method most commonly used to quantify the movement of the human COM during ambulation is the segmental (kinematic) technique. The reason for the widespread use of this method is most likely attributable to its non-reliance on arbitrary estimation of prerequisite variables (such as integration constants used by force platform methods), its applicability to a wide variety of human actions and environments; its ability to yield data in near real time; and its ability to estimate COM location in three dimensions.

The kinematic segmental technique is however reliant on its own subset of assumptions. One of the most important of these is that cadaveric or other artificial data are used to approximate the properties of moving body parts of any subject under scrutiny. Over the last twenty years, a few studies have begun to question the accuracy of segmental derived COM data. In particular Looney *et al* (1990) found that “kinematic methods have been found to be unreliable” whilst Saini *et al* (1998) discovered “physiologically significant differences” between force platform and segmental COM data. Arampatzis *et al* (2000) stated that “the calculations on the basis of kinematic data cannot be recommended to determine efficiency of movement”. These statements suggest that more investigation into the assumptions inherent to the segmental method is warranted.

Before conducting a study on the accuracy of the segmental technique’s ability to locate the human COM, it is important to ask whether there is any benefit in improving the accuracy of COM location measurements. Since COM location and movement data are most often applied to the study of balance, gait energetics and

sporting performance, it is within these fields of study that an answer to this question should be first sought.

Falling is an “all or nothing” event. The degree of error (accuracy) of the measurement of the variables which determine whether or not a patient is susceptible to falling is therefore directly related to the specificity and sensitivity of any potential diagnoses which would be based on that data. In the study of balance it is therefore important to be able to estimate the location of the human COM as accurately as possible. To this end Kingma *et al* (1995) stated that “Since small displacements of the body COM are important in balance control studies, it is essential to obtain standard estimates of the bodies COM”.

Since ambulation is a cyclical event and many cycles are repeated over the time needed for a person to walk or run from one point to another, small errors in the measurement of variables specific to describing each ambulatory cycle may conceivably result in large errors of energy estimates over the entire movement period. It is therefore important to have an accurate measure of COM movement in the study of gait efficiency.

Lastly, since the margins between winning and losing sports events is becoming increasingly small (especially sprinting and endurance running), small improvements in sporting performance are important. Small errors in estimates of COM movement (thought to be an important variable in terms of both sprinting and longer event running performance –Mero *et al* 1992 and Anderson 1996 respectively) may become more and more undesirable.

To my knowledge the degree of accuracy displayed by the segmental technique when locating the position of the human COM, has only twice been quantified in comparison to direct physical measurements (note that this excludes the current studies described in chapters 4 and 5). The first study (Braune and Fischer 1889), found that a segmental estimate of COM location agreed to within 8mm of a direct measurement made on one frozen cadaver in a single body position. The second study found that the segmental technique was able to estimate COM location to within 3.5cm of direct measurements when measured in two subjects, each adopting three body positions (Davis 1973). No study has compared the direct measurement of COM location to segmental estimates in larger groups of subjects or body positions other than what previous authors have referred to as the “normal”, “pike” and “stride” body positions. As a result data that describe direct COM location measurement in any other body position such as in walking and running do not exist.

Despite this the segmental method is today used to estimate COM locations in a variety of body positions which do not fall into the categories of “normal”, “pike” or “stride” body positions. Two possible reasons for the lack of studies that could assess the validity of such measurements is that no direct measurement method for determining the height of COM in an upright individual exists (or may ever exist), which would allow for comparisons to be made, and secondly that if recumbent measurements are used, no method exists to enable subjects to emulate upright body positions.

The fact that no method exists to allow for the direct measurement of upright COM locations during ambulation is a legitimate impediment to quantification of the error that may be present in segmental COM measurements. Indeed, the methods used to estimate COM location in an upright individual today either move that individual into a recumbent orientation, whilst still adopting the original upright body position (which by itself may change the physical properties of the body and therefore the COM location) or use estimates based on datasets derived from recumbent measurement derived estimations of upright COM locations to estimate COM location (the kinematic segmental technique).

In order to further probe the accuracy of the segmental kinematic technique and to describe the results of direct measurement of ambulatory COM location, the studies in this thesis also set out to offer partial solutions and alternative insights into both obstacles (recumbency, and placement of recumbent subjects into “upright body positions”).

To directly measure COM location in different body positions and to assess the agreement between segmental and direct measurements of COM location, measurements are firstly made where extrapolations of recumbent data to upright ambulation are employed. Note that in such cases (chapter 3 and experiments 2 and 3 of chapter 4) where extrapolation of recumbent data to the movement in an upright body position is made, an “untrue” estimate of the upright COM locations are likely to exist when the direct measurement technique is used, due to this extrapolation. However because both the segmental and direct measurement techniques depend on recumbent measurements, such comparisons do elucidate the magnitude of a subset of

error generating factors which are not intrinsic to the “recumbent to upright” measurement problem. Comparisons are also made when no extrapolations of direct measurements to “upright” body positions are used (using both direct reaction-board measurement in chapter 4, experiment 1; and direct suspension measurement in chapter 5). These comparisons show a more holistic assessment of agreement between the segmental and direct measurement approaches, and do so in both supine and sitting body positions. Notice that the studies in chapters 4 and 5 have been conducted using terminology borrowed from conventional metrology but are focused on investigating measurement uncertainty in the traceability chain of kinematic methods with the more modern (GUM) metrological approach.

2.3.1. Aims of the research

The aim of this research is to firstly directly assess the motion of the human COM during ambulation. A second aim of the studies contained in this thesis is to assess the level of accuracy of the (currently) most commonly used COM location measurement technique, namely the kinematic segmental method. The work presented here aims to do so in recumbent and sitting subjects where no extrapolation to upright individuals need be made, and to do so where such extrapolations are made (as is the case during the everyday use of the segmental technique), by applying it to running and sitting subjects. In order to achieve the primary aim of this work, secondary aims of the study include devising two methods for the direct measurement of COM location and displacement in people and to measure the agreement between simultaneous direct measurements and the kinematic segmental method.

Chapter 3

Direct Measurement of the Centre of Mass Location in Walking Persons

3.1. Linking Notes

Many measurements of COM movement in walking subjects have been made using different techniques. None of these have been made using direct physical measurement of COM location. The technique which is used closest to direct physical measurement has been the force platform method.

As described in chapter 2 however, the force platform technique encounters difficulties in the assumptions necessary to define integration constants, and the fact that the double integration process amplifies any error encountered as measurements are made. In addition, force platform methods cannot describe the location of the COM in three dimensional space, but rather only the change in location in reference to an arbitrary unknown location. Such knowledge is however achievable through more direct measurement methods, such as that employed in Chapter 3's study and as such enables additional discussion about the oscillation of COM relative to it's height above the ground (for example) or relative to any other object.

To measure COM movement in walking subjects it was therefore desirable to use a direct measurement method that has been established by others as a benchmark method for the description of COM location. This would provide the alternative data needed to compare existing data which has been generated by other methods.

The measurement accuracy of the reaction-board method used in this study was defined through comparisons between the reaction-board readings and the known movement of a calibration mass. The calibration mass (80kg) COM location was

measured using direct balancing. This mass was then moved about the reaction-board surface to 40 known locations (comparable to the locations over which later measurements would be made). Error was considered to be the difference in location of the COM recorded by the reaction-board system and the known position of the calibration weight COM. These differences between known COM positions and COM determinations of the reaction-board were 0.26 cm (0.01–1.09 cm) for the board length and 0.61 cm (0.01–1.54 cm) for the board width.

One additional source of inaccuracy may be error of placement of the limbs of a subject. A major factor which is likely to contribute to such error is the image distortion of the projected image onto the reaction board. To quantify this latter error, a calibration grid (2.2m long and 1.2m wide) consisting of 50 calibration points was projected back onto itself. The maximal distortion error (of any point) was thereby quantified to be 1.45 cm.

A final source of error of the reaction-board system, may have resulted from human error in placement of limbs, which could for example be due to eyesight defects of experimenters. This source of error was not defined but may have contributed to measurement error.

The study described in this chapter therefore details the most basic of the three studies in this thesis, where the direct measurements of whole body COM location are made and the oscillation of COM during walking is described. In particular, one full walking stride was analyzed for each of 6 adult male subjects, where a mean of 57 ± 5 frames (recorded at 50 frames/s) were investigated. The stark

difference in stride duration shown in figure 2 (between the shortest and tallest subjects), while walking at a speed of $4\text{km}\cdot\text{h}^{-1}$, is likely directly related to the phenomenon that taller subjects have greater stride lengths.

This paper was published subsequent to the paper described in chapter 3. Therefore the detailed methodology of how COM location measurements were made is only discussed later in chapter 4 (chapter 4, sections 2.1 and 2.2). This avoided plagiarism of the previously published paper.

I have placed this empirical study of COM movement in walking subjects, first in the thesis rather than in chronologic order in which manuscript publication occurred. This approach allows a better logical progression to be made from describing COM movement in walking, followed by comparisons between such direct method and more indirect methods, which is a more complex and methodologically detailed subject.

3.2. Original Paper:

McKinon W., Hartford C., and Rogers G. (2005) Direct measurement of the centre of mass location in walking persons. *South African Journal for Research in Sport, Physical Education and Recreation* 27: 57-69.

DIRECT MEASUREMENT OF THE CENTRE OF MASS LOCATION IN WALKING PERSONS

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ABSTRACT

The movement of the whole body centre of mass (COM) is the best single descriptor of the movement of the entire human body. To date however, only indirect or derivative based methods have been used to estimate COM movement in human walking. In this study a direct COM location measurement system, comprising an adapted reaction-board technique consisting of a board supported by four load-cells, is described for determining COM location in walking human subjects. Life-sized projections of subjects in various stride positions are used to place subjects into recumbent static walking positions. Multiple static measurements are used to estimate dynamic COM movement. Data of COM oscillation on six male subjects (age 20 - 23 years) walking at 4 km.h⁻¹ on a motorised treadmill are presented. These data are the first direct measurements of COM oscillation in walking humans over an entire stride. Data found using other, less direct methods are not dissimilar to the data obtained for COM oscillation in this study (median vertical and anterior-posterior COM oscillation during walking 4.1 cm and 5.4 cm respectively, while median COM height was 99.3 cm above the treadmill surface over one stride duration). In addition, we were unable to detect a significant relationship between the magnitude of vertical or horizontal (forward-back) COM oscillation and stature in our subject group ($R^2 < 0.1$; $p > 0.5$).

Key words: Centre of mass; Walking; Gait.

INTRODUCTION

The centre of mass (COM) of the human body is a physical manifestation of the entire human body and is the point relating to the body that requires the most energy to move from one point to another (when changing the body's inertial properties). Measurements of the location of the COM of a person is often carried out in both the clinical and applied sports domains. The applications of such COM data is essential to a variety of scientific applications such as the study of balance, gait, mechanical work and biomechanical efficiency (Cavagna *et al.*, 1964; Benda *et al.*, 1994; Saini *et al.*, 1998). Indeed, in the South African context, recent attempts have been made to further the understanding of quantification balance (Du Toit & Pienaar, 2001) and energy expenditure (Davies & Mackinnon, 2001), both of which are in part reliant on COM movement.

Various methods of estimating COM location and degree of movement now exist, each technique aligned to specific applications. Conventionally, static measurements of the whole body COM location in living people are made using either a knife-edge method (Borelli, 1679) or a reaction-board (Reynolds & Lovett 1909). Dynamic estimations of the changes in

the position of whole body COM are made based on the segmental method of Braune and Fischer (1889), using measurements of the movement of the waist (Belli *et al.*, 1993) or the sacrum (Saini *et al.*, 1998) or derived from ground reaction forces (Shimba, 1984). However, the authors have not found any published data that demonstrate the accuracy of these dynamic measurement methods, where a comparison between known movement of COM and the data obtained using these techniques is made.

Because known positions of COM can be measured in inert objects on a reaction-board, where the actual COM location of the object can be determined, the accuracy of reaction-board measurements is measurable. The reaction-board system is conventionally used to measure COM position in a person in the supine (stationary) position (Hamill & Knutzen, 1995). Reaction-boards have been previously used to measure COM locations of sportsmen in different body positions that corresponded to the body positions seen while performing sports actions (Rasch & Burke, 1967). From this, researchers were able to estimate the different positions of COM in changing postures and could estimate the path of COM during the activity (e.g. diving) (Gowitzke & Milner, 1984). In this manner it was possible to combine data from multiple measurements to generate a description of the dynamic changes in COM location, based on direct COM location measurements.

This study aims to describe the use of multiple static measurements to estimate dynamic COM movement, and to present the first data derived from direct measurements of COM oscillation in walking humans over an entire stride. Secondly, since COM height is sometimes normalised to stature (McDonald & Dapena, 1991; Engsberg *et al.*, 1992) the relationship between COM movement and stature was quantified.

METHODS

Board construction and accuracy

A loadcell based reaction-board (2 m x 1.22 m) connected to a four-channel voltage supply, chopper amplifier system (Eagle Electric, PC 68/4, Cape Town, RSA) was constructed. Amplified signals from each load cell were sampled at 100 intervals per second using a 10-reading moving sample average. Data was processed and logged using a computerised data acquisition system (Biopac MP100, Santa Barbara, USA). The position of the COM of objects placed on the board surface was calculated using standard algebraic methods (Hamill & Knutzen, 1995).

The accuracy of the reaction-board system has been quantified in a previous study (McKinon *et al.*, 2004). Errors of COM measurements were shown to be a median of 0.26 cm (0.01-1.09 cm) for the board length and 0.61 cm (0.01-1.54 cm) for the board width. Differences between recorded and known COM displacements (movement of COM between two points) were 0.05 cm (0.004-0.873 cm) and 0.100 cm (0.006-2.015 cm) along board length and width axes respectively. These errors increase to maxima of 1.95 cm and 2.42 cm for COM positions and displacements respectively when error due to image distortion of our system are included.

Measurements on walking human subjects

Before participating in this study, all volunteering subjects were fully informed of all experimental procedures and indicated their willingness to participate in the study by signing a consent form, written informed consent was obtained in all cases. Experimental procedures were passed by the Committee for Research on Human Subjects of the University of the Witwatersrand (Clearance number M990241). Centre of mass measurements were made on six healthy male volunteers (age 20 - 23 years, body mass 58 - 97 kg, height 170 - 185 cm), all of whom were accustomed to walking on a treadmill. All subjects walked on a motorised treadmill (Powerjog E10, Birmingham, England) at 4 km.h⁻¹ for 2 minutes. The last 10 seconds of each walk was filmed in the left sagittal plane at 50 frames.s⁻¹ using a digital camera (Redlake Motion Meter, Morgan Hill, USA), fitted with a 3.5 mm lens and placed 6 m from the treadmill centre, and at a height equivalent to 1 m above the treadmill surface.

Joint centres of all major body segments were marked using markers that were placed on body landmarks of all subjects. Immediately after walking, recorded images were projected onto the reaction-board from above using a digital data projector (Sanyo PLC XU20E, Osaka, Japan). Life sized images of a line that was drawn along the centre of the treadmill belt was aligned to corresponding marks on the reaction-board, to allow for COM position measurements to be related to positions above the treadmill.

Subjects could observe images of themselves filmed from above whilst lying recumbent on their right sides upon the reaction board, with the aid of an online video system and therefore were able to align their markers (and therefore body segments) to those images, recorded while walking on the treadmill. Two independent observers then refined marker placement by ensuring each marker was in alignment with its image. Once both observers and the subject agreed that all markers were aligned, the subject would lie still and COM co-ordinate data were recorded.

Every five minutes subjects were rested to alleviate any discomfort. Subjects were permitted a pillow to support their heads while positioning themselves, which was removed before data collection. After every ten minutes each load cell was tested and adjusted for potential baseline drift.

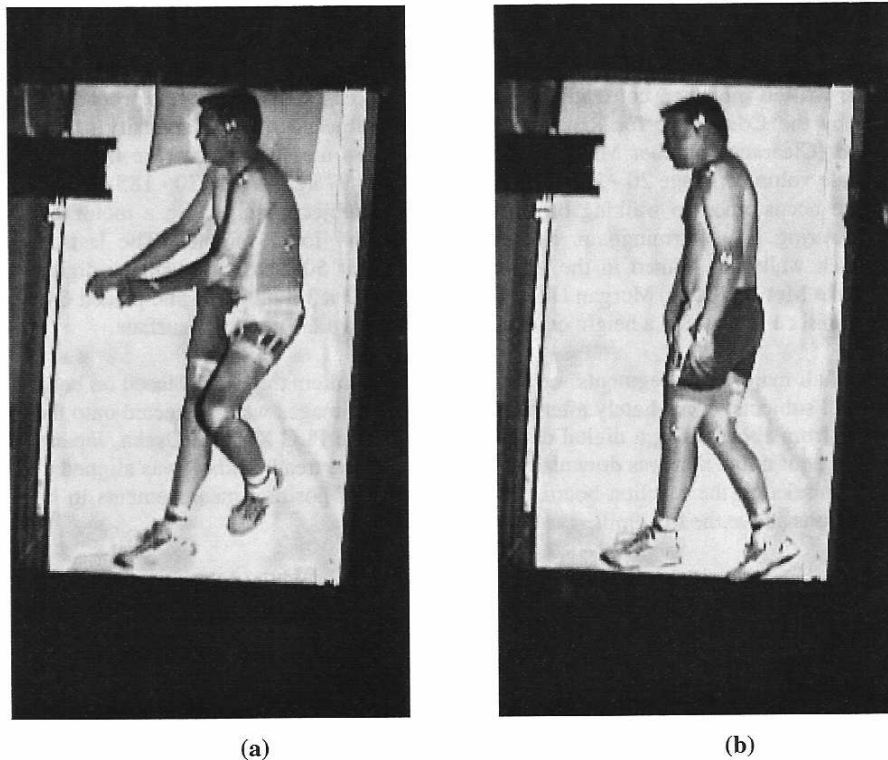


FIGURE 1. PHOTOGRAPHS SHOWING THE EXPERIMENTAL PROCEDURE AS SEEN FROM ABOVE. PHOTOGRAPH A) SHOWS A SUBJECT BEGINNING TO ALIGN HIMSELF TO HIS PRE-RECORDED IMAGE. B) SHOWS THE SAME SUBJECT MINUTES LATER, ALIGNED TO HIS OWN IMAGE (HAVING BEEN AIDED BY TWO OBSERVERS)

Data Analysis

COM data are represented as medians (minimum to maximum in parenthesis). Mean $\pm$ standard deviations have been used in the case of parametric variables (time taken to make measurements and the number of frames per subject). Heights of COM are shown as medians of the median height of all points obtained from one subject over one stride. Oscillation data are calculated from the difference between maximum height of COM above the treadmill and minimum heights for every stride.

RESULTS

TABLE 1. COM OSCILLATION AND HEIGHT OF COM IN SIX WALKING SUBJECTS.

	Median (min.-max.) (cm)
Vertical oscillation of COM	4.1 (3.5-5.8)
Horizontal oscillation of COM	5.4 (4.2-6.4)
Median Height of COM	99.3 (96.3-107.7)

Measurements on all six subject yielded full walking strides (left foot down to left foot down) in all cases. COM oscillation for all subjects displayed sinusoidal patterns of motion over time with respect to COM height above the treadmill (Figure 2). The time taken to make measurements on each walking stride (Table 1) was a mean of 126 ± 42 minutes (mean 57 ± 5 frames). The magnitude of COM oscillation was poorly correlated with stature along both the vertical ($p=0.82$) and horizontal (forward – back axis, $p=0.58$) axes (Figures 3 and 4 respectively). For this reason no attempt to normalise our data to stature was made. The logical relationship between stature and median height of COM over the walking stride was however evident ($p=0.038$, Figure 5).

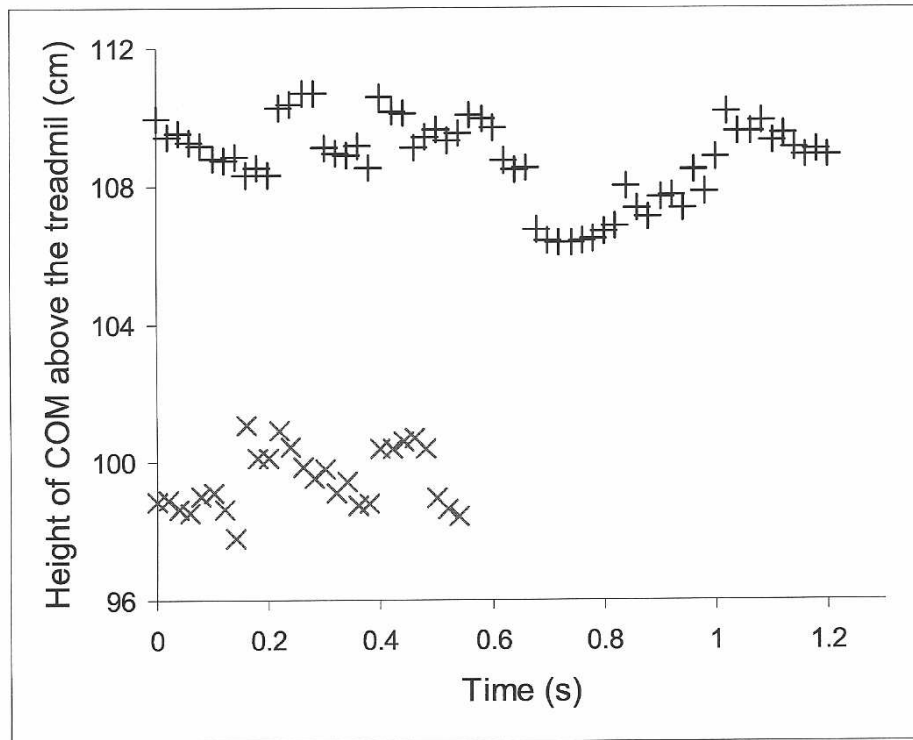


FIGURE 2. VERTICAL CENTRE OF MASS OSCILLATION OF ONE WALKING STRIDE IN TWO SUBJECTS WITH DIFFERING STATURE USING THE REACTION-BOARD METHOD. THE SUBJECT INDICATED BY (+) WAS OUR TALLEST SUBJECT (STATURE 185 CM). THE SUBJECT INDICATED BY (x) WAS OUR SHORTEST SUBJECT (STATURE 170 CM)

DISCUSSION

Reaction-board technique and walking COM data

The data represented here are the first recordings of full COM oscillations for walking strides where the accuracy of measurement of COM location data have been verified by comparisons between measurements made with a COM measurement technique (a reaction-board) and known COM positions. The well known sinusoidal pattern of vertical COM oscillation in the sagittal plane (Cavagna *et al.*, 1975; Shimba, 1984; Iida & Yamamuro, 1987; Crowe *et al.*, 1995; Saini *et al.*, 1998) was observed in all cases (Figure 2). Conventionally such estimates of COM movement have been made by two other methods, namely the segmental and force-platform methods, mainly due to their ability to yield descriptive data in reasonable time.

Force platforms are used to measure the relative movement of whole body COM, utilising a double integration of ground reaction forces (Shimba, 1984; Benda *et al.*, 1994). Force platform methods cannot however estimate the position of COM relative to any reference point in space. The latter method is however dependent on accurate estimation of integration constants, accurate measurement of true mass of the subject as well as the gravitational acceleration constant at the site of measurement. This is because any data errors are amplified during the double integration procedure (errors of the second integral are summated throughout the measurement period).

The segmental technique is also reliant on its own subset of assumptions. One of the most important of these is that cadaveric or other artificial data are used to approximate the properties of moving body parts of any subject under scrutiny. Over the last twenty years, a few studies have begun to question the accuracy of segmental derived COM data. In particular Saini *et al.* (1998: 133) discovered “physiologically significant” differences between force platform and segmental COM data. Additionally, Arampatzis *et al.* (2000: 457) stated that “the calculations on the basis of kinematic data cannot be recommended to determine efficiency of movement”. These statements suggest that more investigation into the assumptions inherent to the segmental method is warranted.

In the past, reaction-board methods have been assumed to be entirely accurate (Dempster, 1955; Davis, 1973). We were however able to demonstrate a minor level of error inherent to the reaction-board approach (McKinon *et al.*, 2004). Notwithstanding this, the use of any other accurate direct measurement methods to measure COM location over a walking stride, such as balancing of suspension of a subject, are unrealistic due to the methodological difficulties. The latter difficulties include extended measurement durations and the need for multiple positioning of a subject for a single COM location data point.

Despite the different approaches used between more indirect methods of COM location measurement and our own, COM data generated by such methods are not dissimilar from our reaction-board data. Vertical oscillation of COM of walking subjects, measured on a force platform varies from 1.7 cm to 3.7 cm (Iida & Yamamuro, 1987; Crowe *et al.*, 1995; Saini *et al.*, 1998). Data from segmental estimates show walking COM oscillations of 2.6 to 4.5 cm (Cavagna *et al.*, 1964; Saini *et al.*, 1998). Both of these are comparable to our median COM walking oscillation of 4.1 cm (Table 1). These figure comparisons are encouraging in respect of the segmental and force platform techniques, which are as yet largely of undetermined accuracy.

Relationship between COM and Stature

Previous studies that have investigated the movement of COM during ambulation have chosen to normalise the location of the COM of their subjects to the stature of the individuals under scrutiny (McDonald & Dapena, 1991; Engsberg *et al.*, 1992). Moreover, it is intuitive to believe that a larger individual should have a proportionally exaggerated gait cycle resulting in a proportionally greater COM height and COM oscillation during walking.

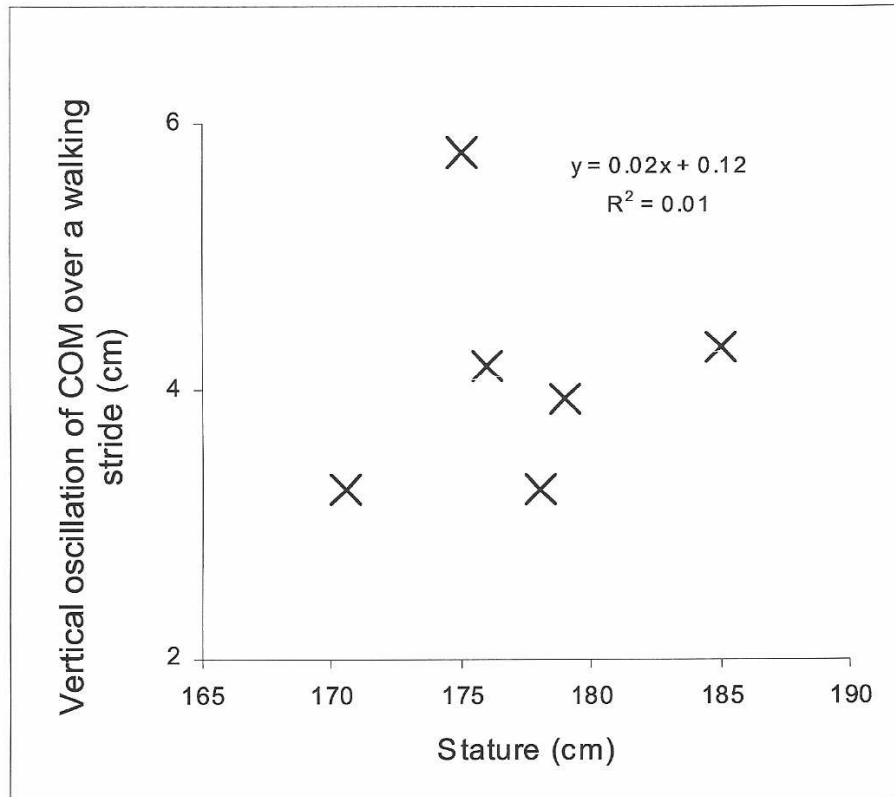


FIGURE 3. SCATTER PLOT SHOWING THE LACK OF A RELATIONSHIP BETWEEN MEASUREMENTS OF SUBJECT STATURE AND THE VERTICAL COM OSCILLATION OVER ONE WALKING STRIDE IN SIX SUBJECTS

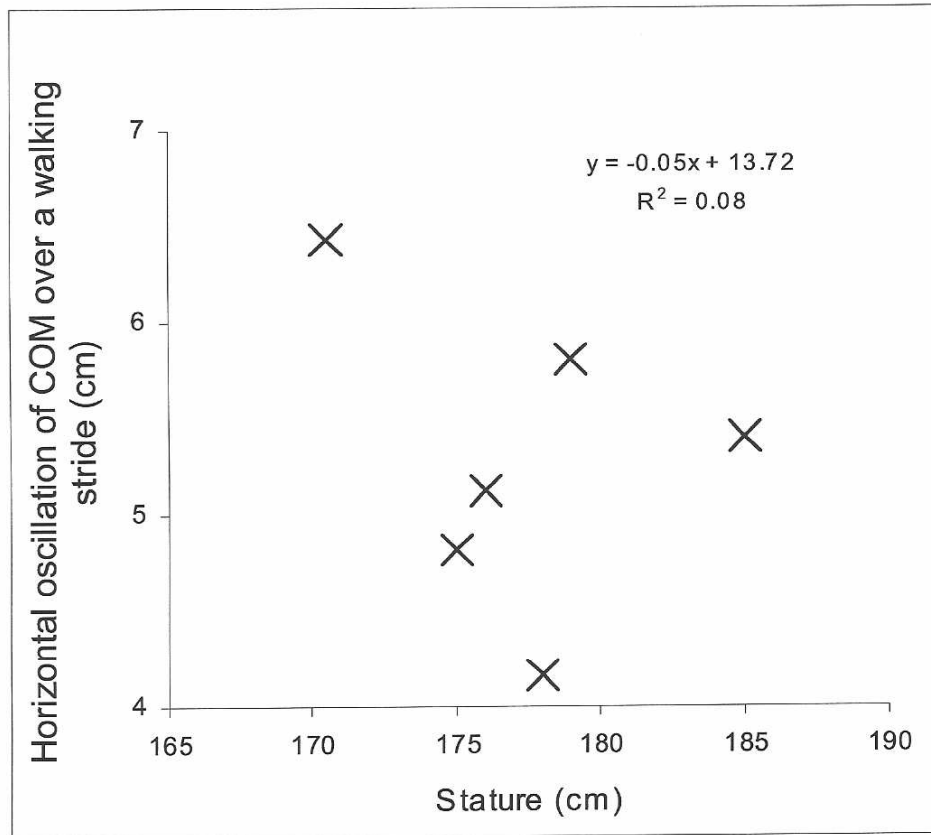


FIGURE 4. SCATTER PLOT SHOWING THE LACK OF A RELATIONSHIP BETWEEN MEASUREMENTS OF SUBJECT STATURE AND THE HORIZONTAL COM OSCILLATION OVER ONE WALKING STRIDE IN SIX SUBJECTS

We found no relevant relationship between the degree of COM oscillation and stature (along both vertical and horizontal axes, Figures 3 and 4). This may be due to the small sample size or because the subjects did not undergo preparatory extensive training and accommodation on the treadmill. The explicable relationship between median stride COM height and stature was however clearly observable (Figure 5).

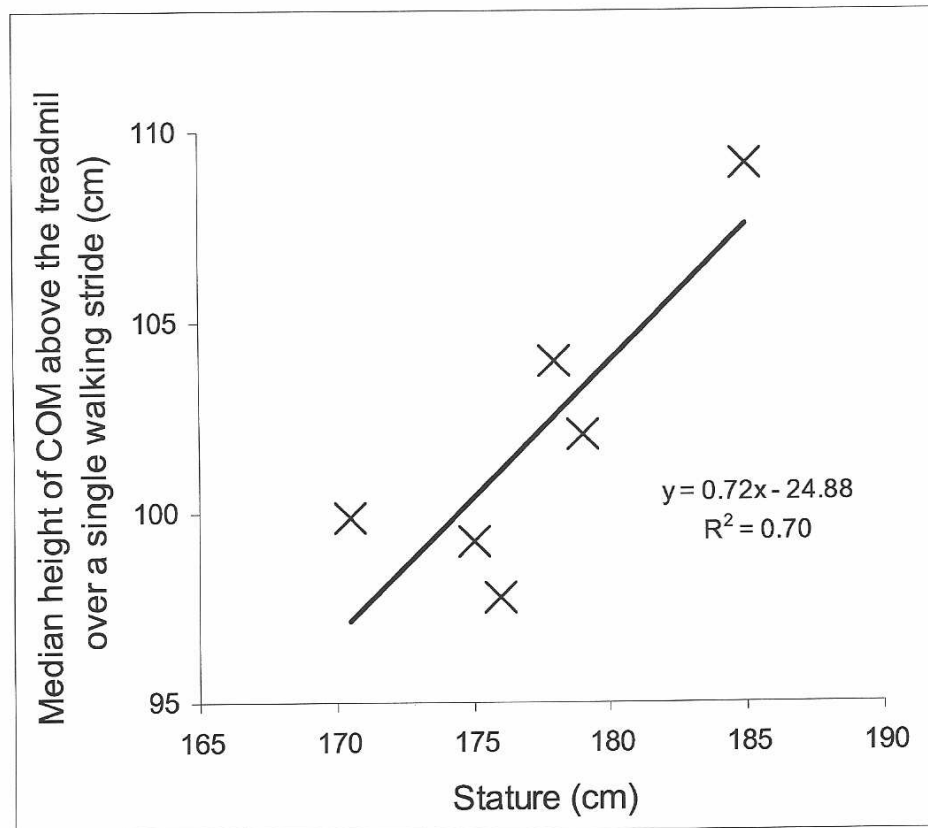


FIGURE 5. SCATTER PLOT SHOWING THE SIGNIFICANT RELATIONSHIP BETWEEN MEASUREMENTS OF SUBJECT STATURE AND THE MEDIAN COM HEIGHT ABOVE THE TREADMILL OVER ONE WALKING STRIDE IN SIX SUBJECTS

In conclusion, this study describes the use of multiple static measurements to estimate dynamic COM movement. The data presented are the first direct measurements of COM oscillation in walking humans over an entire stride. The data obtained for COM median vertical COM oscillation during walking are not dissimilar to data found using other, less direct methods. The use of the methods shown here in conjunction with less direct methods may aid in elucidating the possible sources of error of the indirect techniques. Such studies would make it feasible for correction factors to be devised, enabling greater accuracy of the indirect methods enhancing their applicability in both the sports and clinical realms. In addition, we suggest that future research examine the relationship found between the magnitude of vertical or horizontal (forward-back) COM oscillation and stature in larger subject groups than our own.

ACKNOWLEDGEMENTS

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(Subject editor: Prof. G. van Wyk)

Chapter 4

**The Agreement between Reaction-Board Measurements and Kinematic
Estimation of Adult Male Human Whole Body Centre of Mass Location
during Running.**

4.1. Linking Notes

The study in the previous chapter described direct COM location measurements in walking subjects and uses a direct but arduous reaction-board measurement technique. One of the main aims of this thesis was to compare popular methods of estimating COM location to more direct methods. As a result it was possible to use the same direct measurement methods used to describe walking COM location but in running people, and to simultaneously compare such methods to a segmental kinematic method. In addition to conducting this experiment in running subjects, the research in chapter 4 also looks at the agreement between the direct and kinematic segmental method in non-running static body positions. Lastly this chapter's study assessed the repeatability of a set of running COM measurements and compared such repeatability measurements using the reaction-board and kinematic segmental methods.

Note that the direct measurements described in this chapter were conducted in only two dimensions. In part of the study (experiment 1) however, measurements were not restricted to the sagittal plane but rather reported for the frontal plane, such that multiple different two dimensional analyses could be conducted.

Word Constraints imposed by the publishing journal (*Physiological Measurements*), did not allow for a detailed description of the specific placement of markers referred to (journal page 1343), and are therefore described hereafter. Since only two dimensional models were used in this study, a complete set of markers was first placed in the frontal plane. Each marker was placed on the body surface, directly above the estimated joint center location, which was estimated by visual inspection, using the chart of Lutttgens and Hamilton (1997) [Lutttgens, K and Hamilton, N

(1997) Kinesiology: Scientific Basis of Human Motion, McGraw-Hill, Boston].

Specific joint centres that were marked included: the ankle joint centres, knee joint centres, hip joint centres, shoulder joint centres, elbow joint centres and wrist joint centres. An additional marker used for segmental modelling was the head centre. Markers for identification of the other body boundaries, such as the tips of the toes, fingers and head, were evident on images and were therefore not marked. One final marker was placed arbitrarily on the lateral torso to facilitate placement and alignment of the actual subject when he was moved about the reaction-board. This procedure was repeated in the lateral plane, this time aided by diagrams from both Luttgens and Hamilton (1997) and Plagenhoef et al (1983) [S. Plagenhoef, F. Evans and T. Abdelnour. Anatomical data for analyzing human motion. Research Quarterly 1983; 54:169-178].

Note that GUM (the 1993 International Standards Organization Guide to the Expression of Uncertainty in Measurement) based approaches to measurement comparisons are not yet made in the field of COM biomechanics, therefore classical phraseology and approaches are used (see also section 1.2.2.3). Despite this, the study described hereafter investigated the following aspects of the kinematic segmental method traceability chain and measurement system:

- The overall measurement uncertainty when comparing kinematic methods to a two dimensional reaction-board standard.

- The effects of upright COM data being reliant on recumbent segment inertial parameter measurements.
- The repeatability of COM measurements.

4.2. Original Paper:

McKinon W., Hartford C., Di Zio L., van Schalkwyk J., Veliotes D., Hofmeyr A. and Rogers G. (2004) The agreement between reaction-board measurements and kinematic estimation of adult male human whole body centre of mass location during running. *Physiological Measurement* 25: 1339-1354.

The agreement between reaction-board measurements and kinematic estimation of adult male human whole body centre of mass location during running

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Abstract

The segmental method for estimating the centre of mass (COM) location of the human body has been widely used since 1889. How closely this method agrees with direct measurements of the location and movement of COM during activity however, remains unclear. To test this, a novel reaction-board utilizing life sized projections of human subjects is designed for measuring COM location. Agreement between the segmental method and the more direct reaction-board measurement method is then assessed. Our data demonstrate that the reaction-board system has a physical maximum error of 1.28 cm and 1.95 cm for locating COM along the vertical (board length) and horizontal (board width) axes respectively, and show that the reaction-board and segmental methods agree to within limits of 6.0 cm for the location of COM and to within 5.6 cm for the movement of COM between two points, in recumbent individuals. Applied to running, the segmental method agrees to within limits of 4.8 cm for oscillation of COM and 5.3 cm for stride median COM height. The segmental method agrees with a more direct technique of known accuracy, the reaction-board method, most closely when measuring averaged oscillation over repeated strides, where it displays a measurement error range of 5.1 cm to 0.1 cm in runners.

Keywords: centre of gravity, segmental, balance-board

1. Introduction

The centre of mass (COM) of an object is a point in space through which the translational vector for the momentum of the mass of that object will act. For over 300 years, studies on the measurement of the location of the human body COM have been conducted beginning with Borelli (1679) who found that in a recumbent subject the COM lies 'between the buttocks and the pubis'.

In 1889 Braune and Fischer adapted the work of von Meyer (1863), who investigated the changing COM location upon removal of different body segments, to develop the segmental method of COM determination. Using mathematical reconstruction from cadaver derived data, they determined that estimates of COM location could be made using a method that plots locations of COM of different body segments onto an arbitrary set of axes, when the mass of each body segment in relation to total body mass was known. Braune and Fischer found a 0.8 cm concurrence between their segmental method and actual measurements of COM location, but derived this from only one standing body position (what they termed the 'normal position') and from one frozen cadaver.

Today static measurements of the whole body COM location in living people are conventionally made by using either a knife-edge method (Borelli 1679) or a reaction-board (Reynolds and Lovett 1909). Dynamic estimations of the changes in the position of whole body COM are made using the segmental method of Braune and Fischer (1889), using measurements of the movement of the waist (Belli *et al* 1993) or the sacrum (Saini *et al* 1998) or derived from ground reaction forces (Shimba 1984). Of these the two most commonly used methods of estimating COM oscillations are the segmental and force-platform methods, mainly due to their ability to yield data in reasonable time. However, the authors have not found published data that demonstrate the accuracy of these two methods, by comparing a known movement of COM to the data obtained using these techniques.

Force platforms are used to measure the relative movement of whole body COM, utilizing a double integration of ground reaction forces (Benda *et al* 1994, Shimba 1984). A single force platform cannot however estimate the position of COM relative to any reference point in space. Although suitable for measurements in walking individuals, the force-platform system cannot be used to measure an entire COM oscillation of a running stride because during each stride a runner leaves the ground (flight phase); it is nevertheless possible to estimate COM displacement while in the air using projectile motion theory. The latter method is however dependent on accurate estimation of integration constants, accurate measurement of true mass of the subject as well as the gravitational acceleration constant at the site of measurement. Force-platform measurements of COM displacement also require that the amplitude of force measurement error be very small since force data errors are amplified during the double integration procedure (errors of the second integral are summated throughout the measurement period).

The accuracy of reaction-board measurements is definable since known positions of COM in a rigid object can be compared to data recorded by the reaction-board measurement system. In 1967 Rasch and Burke reported on using the reaction-board to measure COM locations of sportsmen in different body positions that corresponded to the body positions seen while performing sports actions. From this they were able to estimate the different positions of COM in changing postures found in sports activities and to estimate the path of COM during the activity (e.g. diving) (Gowitzke and Milner 1984). In this manner it was possible to combine data from multiple measurements to generate a description of the dynamic changes in COM location. The physical accuracy of the reaction-board system may neglect errors that occur when the COM location is measured in a recumbent position and extrapolated to an upright

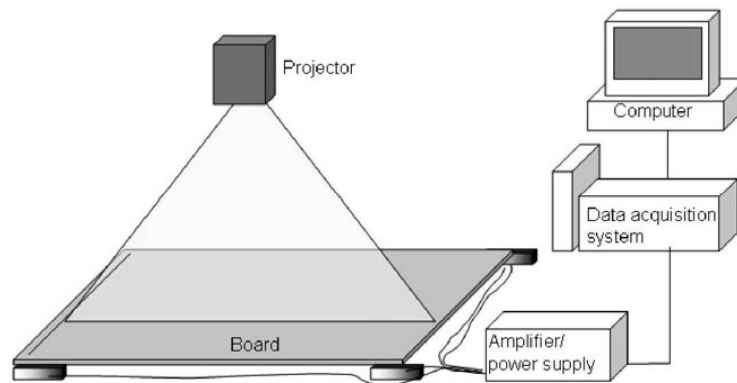


Figure 1. Basic schematic diagram of the reaction-board system.

stature. No gold standard physical method for measuring the COM location of a non-rigid object along the vertical axis (parallel to gravity) currently exists. The true vertical height of a non-rigid object such as the human body, while upright, cannot therefore be directly compared to recumbent measurements. The measurement of the error due to a possible change in the location of the COM of a subject when moving from an upright position to a recumbent (measurement) position may be therefore be unachievable. Despite this, valid comparisons can be made if no extrapolation to upright body positions are made.

The question therefore arises whether the 0.8 cm concurrence found by Braune and Fischer (1889) between the segmental calculation of COM location and their 'actual measurement', shows the same magnitude of error in persons measured in running positions. To our knowledge, there has been no validation of the segmental method in running positions by comparison with a direct measurement of a person's COM (as measured by Braune and Fischer). To investigate the accuracy of COM measurement using the segmental technique over a full stride requires a comparator technique capable of measuring COM over full strides. Therefore, we investigated whether kinematic analysis of COM during running corresponded to measurements made on a reaction-board (an alternate direct technique, of quantified accuracy, and akin to the direct measurement of Braune and Fischer but capable of measuring COM over full strides). We hypothesize that the two methods agree within limits that are acceptable for valid comparisons of COM locations when used to assess differences between or within groups of runners.

2. Methods

2.1. Board construction and accuracy

A metal-reinforced wooden reaction-board (2 m $\times$ 1.22 m) to which four custom-built loadcells were positioned at each corner was constructed. Each load cell was connected to a four-channel voltage supply, chopper amplifier system (Eagle Electric, PC 68/4, Cape Town, RSA). Amplified signals from each load cell were digitally sampled at 100 Hz (10-reading moving sample average) using a computerized data acquisition system (Biopac MP100, Santa Barbara, USA). Standard moment algebra (Hamill and Knutzen 1995) was used to calculate the position of the COM of objects placed on the board surface along the width and breadth axes of the board (figure 1).

To test the accuracy of the reaction-board system a metal calibration weight of 85 kg, (comparable to the body mass of a man) was constructed. The position of the centre of mass of the weight was measured using a knife-edge technique. The weight was balanced on top of two steel pins until the COM of the weight could be discerned to within 1 mm along the axis formed by the two pins. The weight was then balanced a second time with the axis of the pins approximately 90° to the original axis, the intersection of these lines yielding the most accurate measurement of COM possible.

To quantify accuracy of the board measurement system the weight was then moved about the board. The researcher was suspended above the weight in order not to exert any additional forces onto the board while the calibration weight was moved around the board, and to allow the researcher to place the weight accurately onto markers drawn on the board avoiding parallax error.

The movement of the weight of known COM into different positions was conducted in a two square design that comprised an outer and inner square of 30 cm and 10 cm, respectively. Both squares were situated in the middle of the board width. The outer square was placed between 85 cm and 115 cm from the board length measurement axis, roughly corresponding to COM heights of supine humans (Dempster 1955). The inner square ranged between 95 and 105 cm from the measurement axis, roughly corresponding to the 10 cm COM oscillation of a runner (Fenn 1930, Williams and Cavanagh 1987, Morgan *et al* 1991).

Measurements were recorded over 40 points (four repeats of the two square design, two points repeated at the start and end of each square). Error was considered to be the difference in location of the COM recorded by the measurement system and the known position of the calibration weight COM.

Maximal distortion of the projected image was measured by projecting images of a calibration grid back onto itself and quantified to be a maximum of 1.45 cm. In order to estimate the maximal error of COM location measurement due to potential distortion, a subject displaying greater ectomorphy than any of the subjects in the test group was used. The subject was asked to move a single limb (left leg, being of greater mass than the arms) at least 2 cm along either axis, so that an estimate of the maximal error of COM placement due to distortion could be made.

2.2. *Measurements on human subjects*

Three sets of experiments were conducted. The first investigated agreement between measurements of COM location (relative to a fixed reference point) and COM movement (displacement between two successive COM locations) in subjects in different lying positions on a reaction-board versus using segmental analysis of pictures recorded at the same time. The second experiment compared segmental COM data obtained from the analysis of subjects running on a treadmill and reaction-board analysis of the same subjects, in the matching recorded running positions. The third experiment was an extension of the second, where six subjects were analysed for six strides each, but only for two frames per stride, and repeated one week later, to compare the variation in measurement methods over the elapsed week.

2.2.1. Subjects. Approval for experimental procedures was obtained from the Committee for the Research on Human Subjects of the University of the Witwatersrand (clearance number: M990241). Twelve male subjects (age 22–42 years, body mass 57–91 kg, height 170–186 cm) volunteered for the first experiment. The subject group for the second and third experiments also comprised twelve males (age 18–29 years, body mass 58–97 kg, height 170–186 cm), three of whom were from the first experiment.

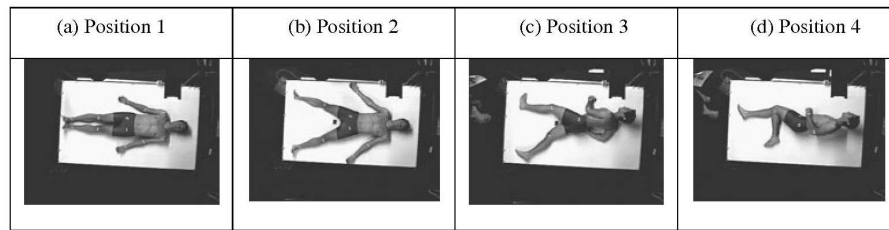


Figure 2. The body positions adopted by subjects in experiment 1, as seen from above on the reaction-board apparatus.

2.2.2. Experiment 1. Subjects were clothed in nylon short cycling pants and had markers placed on appropriate anatomical landmarks (Luttgens and Hamilton 1997) prior to commencement of the experiment. After calibration of the reaction-board loadcells, each subject lay motionless in the supine anatomical position on the reaction-board for 10 s (figure 2(a)) while reaction-board COM data were continuously logged and video images simultaneously recorded from above the reaction-board for subsequent segmental analysis. The subject then moved into a second position by moving his arms and legs laterally (figure 2(b)) and thereafter moved onto the right side and adopted position 3 (figure 2(c)). The last posture adopted is shown in figure 2(d).

2.2.3. Experiment 2. Twelve subjects ran at 15 km h^{-1} for 2 min on a motorized treadmill (Power jog E10, Birmingham, England). During the last 10 s of each run subjects were filmed in the left sagittal plane at 50 Hz using a digital camera (Redlake motion meter, Morgan Hill, USA).

Immediately after running, subjects would lie on the reaction-board in each filmed running position as described below.

Body markers were placed on joint centres and other body landmarks of all subjects. Immediately after exercise, recorded images were projected onto the reaction-board from above using a digital data projector (Sanyo PLC XU20E, Osaka, Japan). Images were enlarged and an image of a line that was drawn in the centre of the treadmill belt was aligned to corresponding marks on the reaction-board, to allow for COM position measurements to be related to positions above the treadmill (see the appendix).

Subjects were able to observe images of themselves filmed from above whilst lying recumbent on their right sides upon the reaction-board, with the aid of an online video system and therefore were able to align their markers (and therefore body segments) to those images, recorded while running on the treadmill. Thereafter two independent observers placed each marker into alignment with its image. Once both observers and the subject agreed that all markers were aligned, the subject would lie still and COM coordinate data were recorded.

Every 5 min subjects were rested to alleviate any discomfort. Subjects were also given a pillow to support their heads while positioning themselves (removed before data collection). After every 10 min each load cell was tested and adjusted for potential baseline drift.

2.2.4. Experiment 3. Six of the twelve subjects from experiment 2 repeated the running protocol twice, one week apart. In this experiment only frames for the highest and lowest positions of the waist marker above the treadmill were analysed (estimating the full excursion of COM), but repeated for six consecutive strides.

All images were stored in digital format for kinematic analysis.

2.3. Kinematic analysis

All measurement frames were calibrated with the use of two-dimensional calibration screens, using least-squares transforms in the form:

$$z = a + bx + cy + dx^2 + ey^2 + fxy + gx^3 + hy^3 + ixy^2 + jx^2y$$

where z is the corrected vertical or horizontal co-ordinate, x and y are distorted image pixel coordinates that correspond to point z in the real world and a through j are fitted calibration parameters. The fit of the above model to calibration coordinates was always better than $r^2 = 0.999\,92$. In the first experiment, video frames contained a picture of the subject and markers along the two axes from which the reaction-board references COM location. The fixed distance between these points also served as a distance reference for each frame. Segment inertial data from Plagenhoef *et al* (1983) were used to construct a 14 segment mathematical model of each position of each subject, as per Luttgens and Hamilton (1997). The resulting COM data were calculated as the perpendicular distance from reference points to the calculated COM location.

For the second experiment the same calculations made to determine COM location were used. In this case the first variable quantified was the distance between the treadmill (a central line running along the length of the treadmill belt) and the COM along the slope of gravity (a plumb line placed in front of the runner, at the same distance from the camera as the central treadmill line). The second variable measured was the horizontal distance from the COM to an arbitrary point in the horizontal field (edge of frame of the filmed images). The plumb line was observable within every frame and was used as an orientation reference as well as a secondary distance reference, since a 1 m long marker was placed along its length.

Data collected included the locations of COM for all filmed frames of a single running stride of all subjects (left foot down to left foot down) and two frames for each of six strides repeated one week apart, on six subjects for the third experiment. The same researcher located the location of all joint centres and reference points in all subjects. Note that all our kinematic analysis arose from skin markers, which may not estimate the position of joint centres as well as some three-dimensional marker systems due to movement of the skin over internal body structures.

2.4. Data analysis

All COM data are medians (minimum to maximum in parentheses). Time taken to make measurements and the number of frames per subject are shown as mean $\pm$ standard deviation. Board COM measurements were corrected for perspective and distortion bias as shown in the appendix.

For experiment 1, comparisons between the locations of COM measured by the reaction-board and segmental techniques were made for each of the four positions along both board length and board width axes. In addition, the movement of the COM from one location to the next was compared along each axis.

Variables calculated from COM location data from 12 single running strides (experiment 2), using the two measurement methods were: vertical and horizontal COM oscillations, median height of the COM for each stride and the maximum change in the velocity of COM over the stride. Heights of COM are shown as medians of the median height of all points obtained from one subject over one stride. Vertical and horizontal COM oscillations are defined as the maximum minus minimum positions of the COM during the running strides along both axes. The maximum change in velocity of COM is calculated as

the maximum difference between the resultant velocities of COM (incorporating movement in both axes) in successive frames.

Values of variables measured in both experiments were compared between measurement methods using a Wilcoxon signed ranks test. In addition, the limits of agreement of data between the measurement methods were quantified using the statistical methods of Bland and Altman (1986).

Experiment 3 compared vertical and horizontal oscillations of COM of six runners over six strides both intra-individually and of the entire group over time. Both variables for each individual were compared between measurement techniques for week 1 (baseline) as well as the change in the variables after the period. Median COM oscillations for the entire subject group were also compared by calculating the median oscillation over six strides for each subject and then calculating the median oscillation for the entire group, from those data, both along the horizontal and vertical axes. Vertical and horizontal oscillations, and change in median oscillations, were compared using a Wilcoxon signed ranks test. Agreement between reaction-board and segmental method data was tested using the method of Bland and Altman (1986) at baseline (week 1), and change from baseline (week 2).

3. Results

3.1. Board construction and accuracy

Differences between known COM positions and COM determinations of the reaction-board were 0.26 cm (0.01–1.09 cm) for the board length and 0.61 cm (0.01–1.54 cm) for the board width. Differences between recorded and known COM displacements were 0.05 cm (0.004–0.873 cm) and 0.100 cm (0.006–2.015 cm) along board length and width axes, respectively. These errors increase to maxima of 1.95 cm and 2.42 cm for COM positions and displacements respectively when error due to image distortion of our system are included.

3.2. Duration of measurements

Time taken to make measurements on each running stride (table 2) was 69 ± 25 min per stride (mean 34 ± 2 frames).

3.3. Experiment 1

Reaction-board and segmental methods of COM location determination report COM location to within limits of agreement of 5.7 cm of each other along the board length axis, and 6.0 cm along the board width axis, for an individual lying in different positions (table 1). The two methods agree to within 3.6 cm and 5.6 cm along the respective axes when reporting movement of COM between two locations (table 1). The median location of COM was shown to be different between the two measurement techniques along the board width axis but only significant along the board length axis when a subject was made to lie on his side. COM movement along the board length axis was significantly greater using the segmental technique compared to reaction-board measurements when a subject moved between supine positions or between supine and lying on his side. No differences were found between measurement methods along the board length axis when a subject moved between positions, lying on his side.

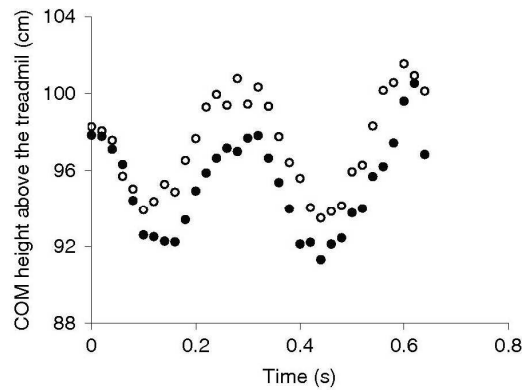


Figure 3. Centre of mass oscillation in the vertical plane of one subject over one stride as measured using the reaction-board (closed circles) and the segmental (open circles) techniques.

Table 1. Differences and limits of agreement between median COM locations and COM movements of the reaction-board and segmental methods in four lying positions.

	<i>p</i> -value*	Lower limit of agreement (cm)	Upper limit of agreement (cm)
COM location along the board length axis			
Position 1	n.s.	-4.3	3.8
Position 2	n.s.	-4.7	3.3
Position 3	0.003	-5.7	1.6
Position 4	0.002	-5.5	1.1
COM location along the board width axis			
Position 1	0.001	-0.2	3.3
Position 2	0.0005	-0.4	3.1
Position 3	0.007	-1.3	6.0
Position 4	0.0005	0.3	4.4
COM movement along the board length axis			
Between positions 1 and 2	0.04	-1.8	0.9
Between positions 2 and 3	0.003	-3.6	1.0
Between positions 3 and 4	n.s.	-2.2	1.8
COM movement along the board width axis			
Between positions 1 and 2	n.s.	-1.4	0.9
Between positions 2 and 3	n.s.	-3.5	5.6
Between positions 3 and 4	n.s.	-3.6	3.5

* Wilcoxon signed ranks test between medians (n.s. = not significant).

3.4. Experiment 2

Figure 3 shows a typical single running stride vertical oscillation of COM over time for a subject using both measurement methods. In this subject, the segmental technique displayed higher COM values and less COM oscillation than the reaction-board. These differences were not representative of all subjects however, as can be seen in figures 4 and 5 (data for the latter subject are represented as an open diamond). Comparisons between measurement methods yielding data derived from COM locations (table 2) for experiment 2 are shown in their entirety in table 3. The segmental method measured both horizontal COM oscillation and maximal change in COM velocity significantly lower than the reaction-board method.

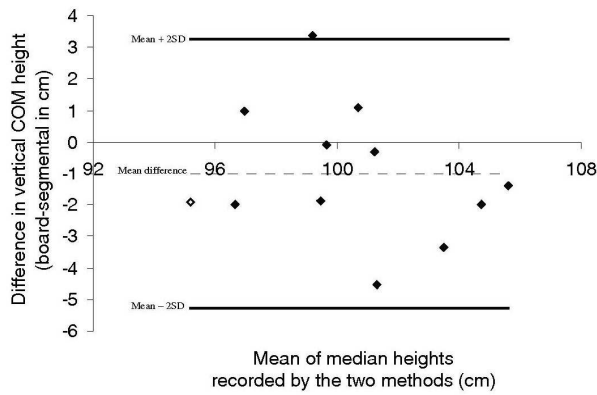


Figure 4. Agreement between the reaction-board and the segmental techniques of measuring the median vertical height of COM over a single running stride using a Bland–Altman plot.

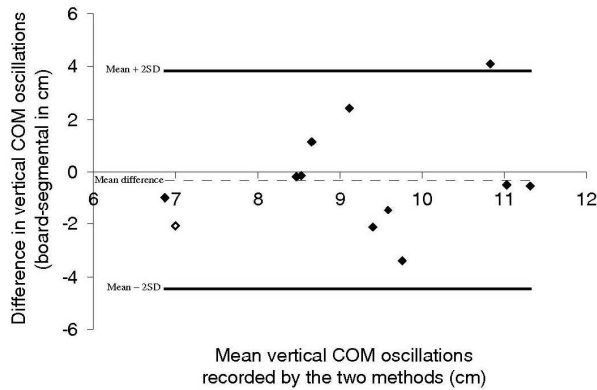


Figure 5. Agreement between the reaction-board and the segmental techniques of measuring the vertical COM oscillation over a single running stride using a Bland–Altman plot.

Table 2. Distribution of COM location derived variables from single running strides on 12 subjects.

	Reaction-board	Segmental method
Vertical oscillation of COM (cm)	8.7 (6.0–12.9)	8.7 (7.4–11.6)
Horizontal oscillation of COM (cm)	5.0 (2.7–7.9)	3.4 (2.1–6.6)
Median height of COM (cm)	100.2(94.2–104.9)	100.3 (96.2–106.3)
Maximal change in velocity of COM (m s^{-1})	1.3 (0.9–2.6)	0.7 (0.6–2.6)

3.5. Experiment 3

The agreement between the abilities of the two techniques to measure COM location data over time are shown in table 4. No differences were found between measurement methods for any of the variables measured, and the agreement was closer between the two techniques than was typical for experiments 1 and 2.

Table 3. Differences and limits of agreement between COM derived variables as measured on a reaction-board and using the segmental method of COM location determination on single running strides in 12 subjects.

	<i>p</i> -value*	Lower limit of agreement	Upper limit of agreement
Vertical oscillation of COM (cm)	n.s.	-4.4	3.8
Horizontal oscillation of COM (cm)	0.02	-2.0	4.8
Median height of COM (cm)	n.s.	-5.3	3.3
Maximal change in velocity of COM (m s ⁻¹)	0.03	-1.3	2.4

* The results of a Wilcoxon signed ranks test between medians (n.s. = not significant).

Table 4. Limits of agreement and values of median two-point oscillation of COM in the horizontal and vertical running planes over six strides (*n* = 6).

	Median values (cm)*	Lower limit of agreement (cm)	Upper limit of agreement (cm)
(a) Week 1 vertical oscillation of COM		-2.0	1.1
The reaction-board	7.8 (4.9–8.1)		
The segmental technique	8.0 (6.2–8.7)		
(b) Change from (a) between week 1 and week 2		-2.6	2.1
The reaction-board	0.2 (-1.1–1.3)		
The segmental technique	0.6 (-0.8–0.8)		
(c) Week 1 horizontal oscillation of COM		-1.7	2.6
The reaction-board	0.9 (0.2–2.4)		
The segmental technique	0.4 (0.2–1.2)		
(d) Change from (c) between week 1 and week 2		-2.7	1.4
The reaction-board	-0.5 (-2.2–0.2)		
The segmental technique	0.0 (-0.7–0.6)		

* None of these was significantly different between measurement techniques.

3.6. Accuracy estimation

Data of the reaction-board are accurate to within 1.95 cm when measuring COM location and to within 2.42 cm when measuring the displacement of COM between two points. Differences between the data generated by the reaction-board and the segmental method of COM location estimation could therefore be due, in part, to this range of the reaction-board's well-quantified accuracy. The greatest limit of agreement between the two different measurement methods (value where the methods differed the most) for variables of COM location or movement is the best (most conservative) estimate of how closely the two methods agree. By adding the maximum error of the reaction-board technique to the greatest limit of agreement between the two methods we establish the widest range of accuracy of the segmental method. Table 5 shows these accuracy ranges. These data suggest that the segmental method is most accurate when measuring changes in COM data over time and least accurate when making single measurements of COM location or movement.

4. Discussion

4.1. The reaction-board

We have described and validated a novel reaction-board system for the accurate estimation of COM location. The data represented here are the first to show full COM oscillations for

Table 5. The limits within which the accuracy of the segmental method is defined.

	Range of accuracy (cm)
Experiment 1*	
COM location	
Board length axis	4.4–7.0
Board width axis	4.1–8.0
COM movement	
Board length axis	2.5–4.6
Board width axis	3.2–8.0
Experiment 2 (applied running data on 12 single strides)	
COM height	4.0–6.6
COM oscillation	
Vertical oscillation	3.4–5.5
Horizontal oscillation	2.4–7.2
Experiment 3 (applied running data on 6 strides, repeated over 1 week)	
Median COM oscillation (week 1)	
Vertical oscillation	1.0–3.1
Horizontal oscillation	0.1–5.0
Change in median COM oscillation (week 1 to week 2)	
Vertical oscillation	1.6–3.7
Horizontal oscillation	0.2–5.1

* No extrapolation of recumbent measurements to upright body positions.

running strides where the accuracy of measurements has been verified by measurements of known COM positions.

Our study demonstrates that the reaction-board system measures COM position to within 1.95 cm, and COM movement to within 2.42 cm. The absolute relevance of this high degree of accuracy is difficult to determine: biologically important variables that arise from COM data in its raw form include COM height and COM vertical oscillation (Williams and Cavanagh 1987, McDonald and Dapena 1991). The magnitude of error demonstrated by the reaction-board system was $\pm 1.5\%$ and $\pm 21\%$ for each of these variables, respectively.

We were not able to ascertain any data that describe or reflect the accuracy of comparable techniques from the published literature. We are therefore not able to comment on the relative accuracy of other measurement techniques compared to the reaction-board system. Comparable apparatus may suffer from inaccuracies inherent to their measurement techniques, such as the amplification of measurement error due to double integration (and estimation of constants inherent thereto) in the case of force platforms, or extrapolation of cadaveric data in the case of the segmental technique. Despite this, COM data generated by such methods are not dissimilar from our reaction-board data. Measurements of runners using the segmental technique produced mean COM vertical oscillation varying between 6.0 and 10.1 cm (Fenn 1930, Cavagna *et al* 1964, Williams and Cavanagh 1987, Morgan *et al* 1991), which are similar to our reaction-board data (figure 2, table 1). These figure comparisons are encouraging in respect of the segmental and force-platform techniques, which are as yet largely of undetermined accuracy.

4.2. The reaction-board technique as a comparator

Physical determination of COM location in a rigid object is measured with greatest accuracy by balancing or suspending the object in an environment where only one force (gravity) acts

on that object. It is however impractical to use such methods for objects that change shape since this would require the object to be balanced exactly for every different shape. In the absence of a better method of COM location measurement, alternative methods that rely on physical laws to detect COM location, such as the reaction-board, are the best methods that can be used to determine the COM location in quasi-rigid objects such as the human body and thereby estimate the accuracy of methods less reliant on physical laws.

The reaction-board method of COM location measurement requires a long duration of data acquisition which renders the reaction-board method an unrealistic tool for routine measurement of COM location on athletes in everyday sports laboratories. However, the known accuracy of the system makes the reaction-board an optimal tool for quantitative research and benchmark validations. One theoretical problem with the reaction-board is that recumbent measurements are used to represent upright locations of COM. The segmental technique also makes this extrapolation, since the calculation's fixed data rely on measurements made on 'recumbent' frozen body parts. Thus experiment 1 of our study was devised so that comparisons can be made without requiring this extrapolation: subjects lie on the reaction-board and both the segmental and reaction-board techniques are applied to measure COM location in the recumbent position. In experiments 2 and 3 the extrapolation is used by both measurement techniques, as required for application to running subjects.

We were not able to test observations of the agreement between the reaction-board and the segmental methods in planes other than the sagittal because of the stability needed for a subject to remain still on a reaction-board. In fact, accurate direct methods of COM location measurement without the variable of gravity are not possible with any currently available COM measurement apparatus.

A reaction-board derives the location of the COM in a stationary object placed on its surface by using simple moment calculations (Reynolds and Lovett 1909). As such, data derived from this method arise from the actual properties of the body parts of a subject lying on the surface of the reaction-board, rather than from assumptions that are inherent to the segmental technique's calculations. The latter method is largely based on extrapolation from data sets that describe thirteen or fewer cadavers, which may not be representative of the morphology of a particular subject under scrutiny.

4.3. Accuracy of the segmental technique

Interpretation of the agreement found between the two techniques depends on what is considered a biologically relevant difference between the data yielded by measurement methods. In the case of COM data, a biologically relevant difference needs to be viewed in the context of the application of such data in the real world. Applied to sports performance, any difference in COM oscillation or COM height, which could yield a positive or negative change in performance might be considered relevant.

Published data on what may be considered relevant changes in running COM data are rare. Studies are usually conducted in healthy subjects so that COM movement abnormalities of large amplitude are not usually seen. In addition, the relationship between COM oscillation and athletic performance may not be statistically significant (Cavanagh *et al* 1977). What constitutes a biologically relevant difference between two COM measurements' data, although theoretically important to running performance, is therefore empirically unclear. For this reason we comment only on the levels of agreement between measurement methods and on accuracy, without speculating about the biological relevance of the magnitude of the difference.

4.3.1. Experiment 1. In experiment 1 we have shown that the reaction-board and segmental methods agree to within 6.0 cm (table 1), when COM locations are estimated either in supine positions or when subjects are made to lie on their right side. The data were all significantly different between measurement methods along the board's width axis, which may be due to the relatively greater error of the reaction-board along this axis. Of interest, significant differences between the measurement methods when determining COM location along the board's length axis were only seen when subjects were made to lie on their sides. This difference between the methods when a subject is made to lie on the side may be due to the reliance of the segmental method on inertial data of bodies in a supine orientation, whereas the reaction-board will reflect the lateral orientation of the subject under study. Measurement of COM displacement as subjects move between recumbent positions showed a better agreement between the measurement methods than measurements of COM locations.

4.3.2. Experiment 2. Experiments 2 and 3 (tables 2 and 3) differ from experiment 1 in that both the segmental and reaction-board methods here extrapolate measurements from recumbent to upright individuals. The application of multiple reaction-board and segmental method estimations of 'freeze frame' COM locations to estimate the path of COM movement in non-recumbent actions has been performed for a long time (Groves (1950) and Fenn (1929), respectively). More recently, similar measurements made on walking subjects, using a force plate which does not extrapolate to upright positions, showed a statistically significant difference from those of the segmental method (Saini *et al* 1998). In experiment 2 we have shown that reaction-board and segmental measurement methods of estimating the vertical COM oscillation and median COM height for full single strides were not statistically significantly different, although there was a difference in agreement of 4.4 and 5.3 cm for each variable respectively (table 3). The results of Saini *et al* (1998) may differ from our findings due to the different modes of locomotion and/or study design used. For running movements we show that the segmental method of COM location estimation is able to define COM vertical oscillation to within 5.5 cm and to discern the location of the median height of COM to within 6.6 cm (table 5).

The lesser agreement for horizontal COM oscillation in the 12 full running strides measured during experiment 2 using the segmental system is, as was the case for experiment 1, in part due to the relatively larger reaction-board error of the measurement of the movement of COM along the board width axis (2.42 cm as compared to 1.06 cm in the board length axis). Despite this, the bias in the segmental method for estimating COM horizontal oscillation is at least 2.4 cm (table 5). This bias may be due in part to the artificial homogeneity of data created by the segmental method, since body parts in all positions are expected to have identical properties. A body part may however have variable characteristics; segments for example can alter their shape (such as during muscular contraction or loose tissue distension) or change their internal tissue composition (for example vascular engorgement or changing tissue mass distribution as bony levers change angles). These factors are particularly true of the horizontal ('forward-back') plane because limb movement along this axis is greatest during running. The reaction-board is also not able to detect all of these changes (since subjects are not running at the time of measurement), but a greater amount of the realistic changes in the properties of body segments is detected, in comparison with the segmental method. Our data illustrate that the segmental method of COM location determination agrees with the more direct reaction-board technique in measuring horizontal COM oscillation to better than 7.2 cm.

The maximal change in COM velocity is considered to be an important variable potentially related to performance in runners (Dillman 1975, Morgan *et al* 1991). The lower values for this

variable yielded by the segmental method compared to the reaction-board is likely because it depends in part on the ability of the measurement methods to determine the horizontal COM movement (horizontal COM oscillation between frames), which the reaction-board is inherently better able to detect.

4.3.3. Experiment 3. In experiment 3 the use of repeated measurements of COM vertical oscillation over six strides reduced the influence of outlier data points and therefore predictably enhanced the agreement between the measurement methods, as can be seen by the narrow limits of agreement (table 4). This is also true for the changes in vertical oscillation over the one-week period. Horizontal oscillation data are not shown because the highest and lowest points of the waist during each stride chosen are almost identical in the horizontal (forward–backward) plane as a subject runs on the treadmill as can be seen from the median location data for week 1 (table 4).

The limits within which the accuracy of the segmental method is defined are shown in table 5. Our data suggest that the segmental method is best suited to measurements of movements or locations of COM averaged over at least six strides, where the accuracy of the system is better than 5.1 cm and may even be as good as 1 mm. This level of accuracy is also found when measuring the change in these variables over time.

An interesting observation arising from our data is that the agreement between the two techniques is similar irrespective of whether the methods are applied to recumbent lying positions or extrapolated to upright data. We ascribe this to the fact that both methods require data to be generated from measurements of recumbent COM measurements, and therefore both may share some common bias. Note however that our measurements were only made in the sagittal plane and do not take account of the change in its position due to adduction or abduction of the hip of the supporting leg during running.

5. Conclusions

In conclusion we have shown that the segmental estimation of COM location agrees with reaction-board measurements to within 6.0 cm and is therefore able to estimate COM location in recumbent persons with an error of between 8.0 cm and 4.1 cm. Agreement between the two methods of measuring COM movement in recumbent persons is within 5.6 cm, which shows that segmental analysis can estimate the movement of COM of a recumbent subject with an error of between 8.0 cm and 2.5 cm. When the segmental method is used to measure COM movement in single strides of running, the accuracy of the method improves slightly for both COM height and oscillation (agreement: 5.3 cm and 4.4 cm, respectively). The greater COM movement measurements recorded by the segmental method result in larger values of COM movement derived variables such as the maximal change in COM velocity. The segmental method is most accurate when measuring averaged oscillation over repeated strides where it displays a measurement error range of between 5.1 cm and 0.1 cm.

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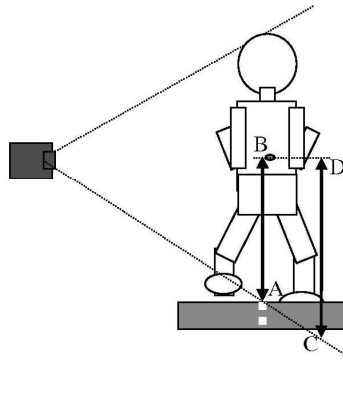


Figure 6. Schematic diagram of an individual running on a treadmill as seen from behind.

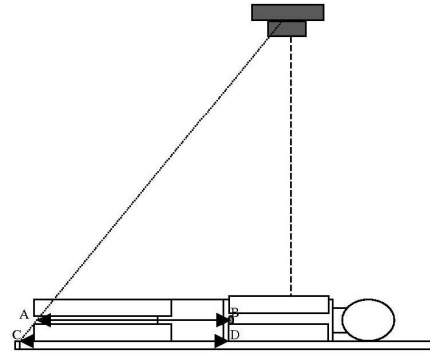


Figure 7. Schematic diagram of a subject lying on the reaction-board.

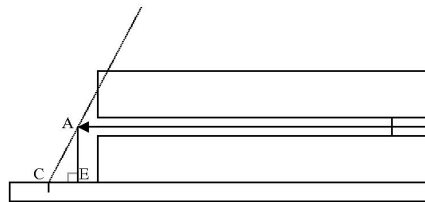


Figure 8. Construction of a triangle to derive the correction factor (CE).

Appendix

To place a subject in perfect alignment with an image of that subject on the reaction-board, the image on the board needs to be larger than life size (since the subject lies closer to the projector than the board surface). Additionally, the image (enlarged image) needs to coincide with the reference points on the board so that measurements on the board can relate to a standing subject. The board image however, is, as has been stated, not its true size. The corrections for both of these factors have a common solution through correction factor 'CE', described below.

The distance from a line drawn down the middle of the treadmill (line A, figure 6) and the COM of a subject is the best estimate of the height of the COM (point B) above the treadmill when a subject is filmed in the sagittal plane (line AB, figure 6).

The image of the treadmill line is projected onto the board surface, which lies to the right of the subject when he lies on his side (line CD, figure 7).

The distance of line CD is the measurement made on the reaction-board and is the distance from the treadmill line image to the COM as measured. The difference in length between line CD and line AB (the actual height of COM above the treadmill) is solved by constructing a right-angled triangle as shown in figure 8. The triangle is defined by introducing point E, that lies on line CD so that length DE is the same as AB. Line CE is therefore the correction factor to correct CD to AB. Length CE can be solved using the following formula: $\text{length CE} = \tan(\text{projection angle}) \times \text{length AE}$. The projection angle (at point A), is easily calculated from

measurements of the height of the projector above the reaction-board and the distance between the perpendicular height of the projector and reference point C. To estimate length AE, we assume a symmetrical subject. An objective (if somewhat arbitrary) estimate of the length AE (BD) is the horizontal distance between the centre of the umbilicus and the side of the body.

Note that the correction factor CE is calculated before the subject lies on the board, and the size of the image is enlarged by exactly that amount. With the appropriate correction of the image, body markers coincide with the actual markers found on the subject because the distances between markers are accurately reproduced by the image. This was the case in all our trials.

Lastly, it is important to quantify any error that may be apparent due to optical distortion. In our case the maximal distortion along the line of COM height (from the image centre to the treadmill line) was 1.4 cm. All data collected for COM height were therefore reduced by this amount.

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Chapter 5

Adult Male Human Whole Body Centre of Mass Location Measurement:

**Magnitude of Differences between Segmental Kinematic Estimations and Direct
Suspension Measurements.**

5.1. Linking Notes

In the previous chapter (4), a novel reaction-board approach was used for comparisons of direct and kinematic segmental measurement methods for the measurement of COM location in different two-dimensional body orientations. Modern kinematic methods however have a three dimensional capacity which may possibly differ in accuracy to two dimensional kinematic approaches.

Additionally, whilst a previous landmark study has used a reaction-board technique as a standard benchmark measurement method (Davis 1973) the studies in chapter 4 found that this system had its own inaccuracy (approximately 2.4cm overall measurement uncertainty).

In this final study we therefore elected to use the very first benchmark comparator, an even more direct measurement method, which could thus be used as a reference standard method. We used that same method used to originally establish the segmental kinematic method (Braune and Fisher 1889), which was also the method used to measure body segment locations in the dataset most commonly used for kinematic modelling today (Dempster 1955).

Note that in order to conduct three dimensional kinematic measurements, computerised algorithms needed to be written based on established image processing, image analysis, and three-dimensional joint centre locating techniques. With some technical assistance I was able to write such algorithms, the major subroutines of which were concerned with image analysis and marker tracking, conversion of tracked marker locations into a three dimensional model and lastly the calculation of

joint centre and centre of mass locations. These major algorithms were written in Matlab (version 7 release 14) and are attached as part of Appendix 2 as follows:

- Appendix 2.1) Image analysis and marker tracking graphical user interface.
- Appendix 2.2) Direct Linear Transformation implementation algorithm for multiple body markers which allows for marker locations into a three dimensional model.
- Appendix 2.3) Algorithm for the calculation of joint center and center of mass locations based on established marker set conventions.

Note once again, that because GUM (the International Standards Organization Guide to the Expression of Uncertainty in Measurement) based approaches to measurement comparisons are not yet made in the field of COM biomechanics, therefore classical phraseology and approaches are used (see also section 1.2.2.3). Despite this, the study described hereafter investigated the following aspects of the kinematic segmental method traceability chain and measurement system:

- The overall measurement uncertainty when comparing kinematic methods to a three dimensional suspension measurement standard.
- Two segment inertial properties used to model the whole body COM comparing different approaches (cadaver derived and live human derived approaches) were compared.
- Measurement uncertainty was tested for any possible relationships with anthropometric models.
- The variation in measurement uncertainty of the suspension system over time was assessed.

At the time of this Thesis submission, this chapter is under review at *The Journal of Biomechanics* as an original article. For the purposes of this thesis figures and tables as well as their captions have been placed in the appropriate places within the text of the article.

5.2. Original Paper:

Adult male human whole body centre of mass location measurement: magnitude of differences between segmental kinematic estimations and direct suspension measurements.

Adult male human whole body centre of mass location measurement: magnitude of differences between segmental kinematic estimations and direct suspension measurements.

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Abstract

The location of the human whole body centre of mass (COM) is now frequently measured in the scientific, clinical and various applied biomechanical realms. To assess accuracy of the commonly used kinematic (segmental) modelling method of estimating COM location we compared two such models against direct suspension-based COM location measurements. We used kinematic models derived from direct measurements made on cadavers and indirect gamma scanning methods in live humans. In fifteen healthy male subjects the two kinematic model estimations were statistically significantly different to simultaneous direct measurements of COM location (suspended sitting positions). The cadaver based kinematic model was statistically significantly more similar to the direct suspension method than the human based kinematic model (mean differences $31 \pm 13\text{mm}$ and $92 \pm 17\text{mm}$ differences, respectively). Differences were not correlated to whole body mass, body fat or body water. In conclusion, kinematic (segmental) estimations of COM location differ significantly from simultaneous direct suspension measurements. Additional research to understand the factors behind these differences will facilitate improvements in the accuracy of kinematic estimations of COM location, an important biomechanical tool in several applied areas for which kinematic measurement techniques are in widespread use and uniquely offering three dimensional COM location capabilities, applicability to diverse environments and suitability to all human actions.

(Word count: 207 words)

1. Introduction

For hundreds of years since its first measurement [17], the usefulness of the location of whole body centre of mass (COM) data was confined to theoretical science. In 1930 Wallace O. Fenn, first used this data to quantify tangible COM derived variables, when calculating “running expenditure of energy” [59]. Nowadays COM location data have a number of directly applicable purposes, including: diagnosis of pathology [32, 48, 71, 72], a tool to estimate external work [28, 108] and a variable with specific usefulness in a number of different sporting applications [7, 34, 100, 104].

Braune and Fischer (1889) first used knowledge of the location of body segments as well as their inertial properties to estimate COM location. Today the latest incarnation of the Braune and Fischer segmental method is one of the most widely use methods to estimate COM location in a great variety of population groups (varying in gender, age and ethnicity) and human activities. The widespread scientific use of the segmental kinematic method arises from a quick data processing capacity, applications in diverse environments (such as water and outer space) and applicability to most human movement including ambulation, stillness or movement through the air.

Using a method of body suspension, Braune and Fischer showed that, error between the segmental method and actual measurements of COM location about 8mm. Today, many comparisons between COM location data from segmental kinematic modelling and other methods to estimate COM location exist. These comparisons include methods making use of single sacral markers [13, 126], ground reaction force methods [14, 65, 70, 92] and reaction-boards [41, 103]. One potential issue with using

all the above methods as benchmarks is that the theoretical error of these techniques is, for the most part, unknown. Indeed, most techniques used as benchmark comparators rely on other devices to get their data (e.g. scales, photocells and load cells), all of which have their own inherent errors.

The most direct methods of COM location measurement are balancing and suspension. No studies using current technology compare balancing and the segmental method. This is likely due to the technical difficulty required to make such measurements, including difficulties in placing a pivot and keeping a subject motionless for multiple measurements. Only one study compares the suspension method, the study that founded the segmental method [19]. Countless modifications to the original methods of Braune and Fischer exist, notably recent use of: lens aberration correction methods; high speed digital photography; algorithms to estimate the locations of joint centres; three dimensional transformation methods, and automated marker tracking.

We conducted a study to assess whether modern segmental kinematic models used to estimate COM location yield results consistent with a simultaneous direct suspension method. We hypothesise that errors using current segmental kinematic model techniques are less than the known 8mm error described by Braune and Fischer. We further hypothesise that COM locations estimated using kinematic segmental models are similar between those derived from cadavers versus human data. We describe whether potential errors are correlated to selected anthropometric characteristics of our subjects.

2. Methods

2.1. Subjects

Sixteen healthy male subjects from either Caucasian or African ancestry (ages 25 ± 5 years, body mass 75 ± 14 kg, height 1.73 ± 0.06 m) participated in this study only once both written and oral informed consent was received (Local ethics clearance: M050107).

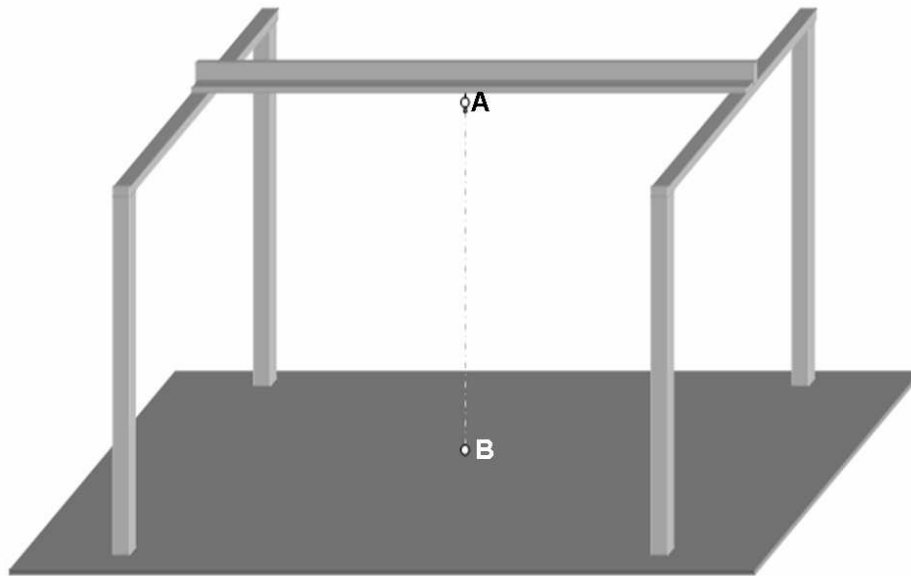


Figure 1. Schematic diagram of the suspension device for whole body centre of mass location determination.

2.2 Suspension system for determining COM location

At the centre of the crossbar of a metal frame 1m high (Figure 1), a 50mm long, 5mm thick metal cord was fastened, from which subjects could be suspended using a harness. Half way along the length of this cord a retroreflective marker was placed (point A, figure1). Before and after each COM determination, a plumb line was attached immediately below point A, enabling the projection of point A along the line of gravity, onto the floor surface (point B, figure1), to be identified. When a subject

was suspended under point A and was freely hanging (not in contact with any other object aside from the connection point A), the subject's COM oscillates around the line joining A and B. From this, conventional kinematic methods (detailed later) were used to determine the locations of points A and B, thereby describing line AB.



Figure 2. A subject sitting in the suspension apparatus.

2.3 Procedure and image acquisition

Body markers were applied to appropriate body landmarks for whole body kinematic analysis per [40, 71]. The marker set included a full body modelling arrangement of markers that were placed on the following body sites: each second metatarsal, the lateral maleoli, two shank wands, the lateral femoral epichondyles, two thigh wands, the left and right anterior suprailiac spines, the sacrum, the 7th cervical vertebrae, the 10th thoracic vertebrae, the notch between clavicals, the sternal notch, acromia, Lateral humeral condyles, thumb-sides of wrists bars, little finger-sides of wrists, the

third metatarsal heads, left and right temples on band, left and right parietal bones posterior on the head band. Subjects were fitted with a light weight (300g) climbing harness (Pandion C29, Petzl, Crolles, France). Suspension point B was identified and subjects were lowered into a seated position inside the suspension apparatus (Figure 2, 3). Pilot testing showed that this body position was most comfortable for subjects and facilitated a near-motionless body position.

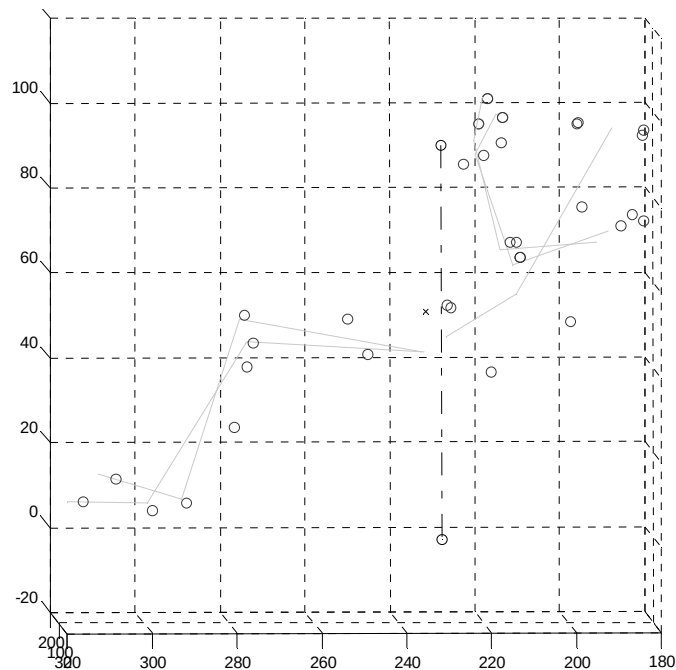


Figure 3. A graphical representation of a 3D model of one subject. Circles indicate marker positions, (including points A and B of the suspension apparatus, which define the suspension axis, represented by a broken line). The cross indicates the segmental estimation of whole body COM in this subject.

Images were captured from 6 digital camcorders (Sony HC21E, Osaka, Japan) at 25 frames per second (note that all measurements are quasi -static) for 12 seconds.

2.3.1 Image processing and segmental kinematic analysis

Image processing and analysis was conducted using pre-existing, and purposefully designed, Matlab7 (Mathworks, Natick, USA) based algorithms. All cameras were calibrated for lens aberrations using established methods [156]. Immediately before each subject's data collection session a 12 point calibration frame (1.8 m square) was placed around the suspension apparatus and data collected for definition of direct linear calibration constants.

A Matlab centroid based automated image thresholding and marker tracking algorithm identified marker centroids in each frame. Each marker was reconstructed in three dimensions using a modified direct linear transform algorithm [76] and reconstruction algorithm [123]. The resulting three dimensional marker coordinates were used to define the limits of 15 body segments (feet, lower legs, upper legs, hands, forearms, upperarms, pelvis, thorax and head plus neck).

Table 1. Segmental inertial parameters used in this study.

Body segment	<u>Dempster Model^a</u>		<u>De Leva/Zatsiorsky Model^b</u>	
	Segment Centre of mass location (proportional distance from distal border)	Segment proportional mass	Segment Centre of mass location (proportional distance from distal border)	Segment proportional mass
Right hand	0.506	0.006	0.2100	0.0061
Left hand	0.506	0.006	0.2100	0.0061
Right forearm	0.430	0.016	0.5426	0.0162
Left forearm	0.430	0.015	0.5426	0.0162
Right upper arm	0.436	0.027	0.4228	0.0271
Left upper arm	0.436	0.026	0.4228	0.0271
Right foot	0.249	0.014	0.5585	0.0137
Left foot	0.249	0.014	0.5585	0.0137
Right lower leg	0.434	0.045	0.5541	0.0433
Left lower leg	0.434	0.045	0.5541	0.0433
Right upper leg	0.437	0.096	0.5905	0.1416
Left upper leg	0.437	0.097	0.5905	0.1416
Head and Neck	^c	0.079	^c	0.0694
Thorax	^c	0.503	^c	0.4346

Data sources: ^a Zatsiorsky (2002); ^b de Leva (1996).

^cHead/Neck and Thorax centre of mass locations calculated as per Gutierrez *et al* (2003)

Two different models were used to estimate the relative masses and three dimensional segmental centre of mass positions (table 1). The first model originates from the cadaver based data of Dempster [47] as reported by Zatsiorsky [154]; hereafter abbreviated as the DT model. The second kinematic model is based on the modified data of Zatsiorsky and Seluyanov [155], as modified by de Leva [44], being a model more closely derived from anthropometric measurements of live humans (ZTDL model).

To compare the kinematic estimates of COM location to the line defined in the suspension technique (line AB: the suspension axis), the shortest distance between the line and the kinematically calculated COM point was constructed (a line perpendicular to line AB, incorporating the latter COM point). This distance was considered the maximum possible concordance between the two techniques because the vertical COM height can not be directly measured. This distance is therefore the only possible objective measure of simultaneous concordance between the two methods and used as an objective error measurement of the segmental kinematic COM estimates.

2.3.2 Accuracy of the kinematic system

To assess the accuracy of the system a wand supporting two markers 200 mm apart, was randomly moved through the area under the suspension apparatus for 12 seconds (akin to the measurement period of experimental data). Error in the measurement system was estimated as the difference between the known and kinematically calculated distance between wand markers.

2.3.3. Percentage body fat, mass and water determination

Within 48 hours of the COM analysis dual-energy X-ray absorptiometry (DXA) scans were conducted for body fat determination using standardized patient positioning and analysis (Scanner model QDR 4500A; Hologic Inc, Bedford, MA). Immediately preceding each trial, body mass and height were measured using a calibrated height gauge (Seca Corp, Germany) and a calibrated medical balance scale (Seca alpha, model 770, Germany), followed by supine whole body bioimpedance measurements (Biostat, Douglas, UK) for body water content.

2.4. Data Analysis

All data are mean $\pm$ standard deviation unless otherwise specified. Comparisons between kinematic models and the suspension axis were conducted using a single sample paired Students t-test against zero and Bonferroni correction for multiple comparisons. Comparisons between the DT and ZTDL models were compared using a paired Students t-test with Bonferroni correction to correct for previous comparisons. Pearson's product-moment correlations assessed the relationship between kinematic measurement error and body mass, fat and water percentage.

3. Results

1.1.1.1. 3.1. Accuracy of the kinematic system

Differences between the known wand inter-marker distance and the inter-marker distance calculated by the kinematic measurement system was $3.0 \pm 5.6\text{mm}$ corresponding to a root mean square (RMS) error of 5.7mm.

1.1.1.2.

3.2. Differences between direct suspension and kinematic COM estimates

Figures 4 and 5 are representative of the oscillating pattern of the distance between kinematic COM location and direct suspension axis measurements in all subjects. The degree of oscillation was twice the standard deviation of the distance between kinematic COM location and the suspension axis. The amplitude of oscillation data varied between 3.1mm and 7.2mm (mean $4.8 \pm 1.1\text{mm}$) for the ZTDL model and between 3.6 mm and 6.8 mm (mean $5.1 \pm 1.0\text{mm}$) for the DT model.

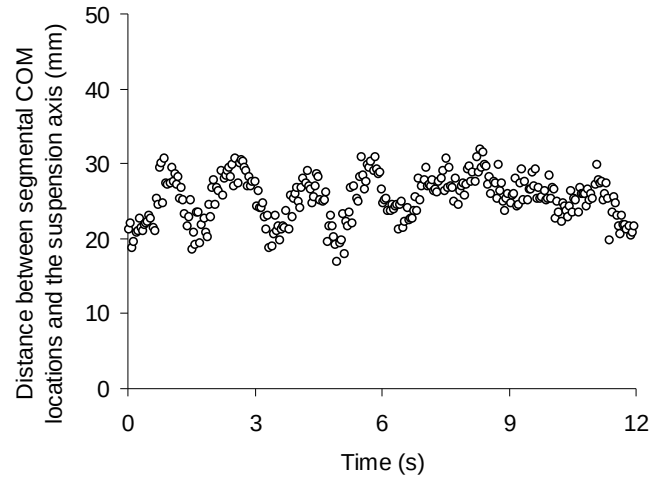


Figure 4. The distance between kinematic COM location (Dempster model) and the direct suspension axis for a single subject over 12 seconds of data collection.

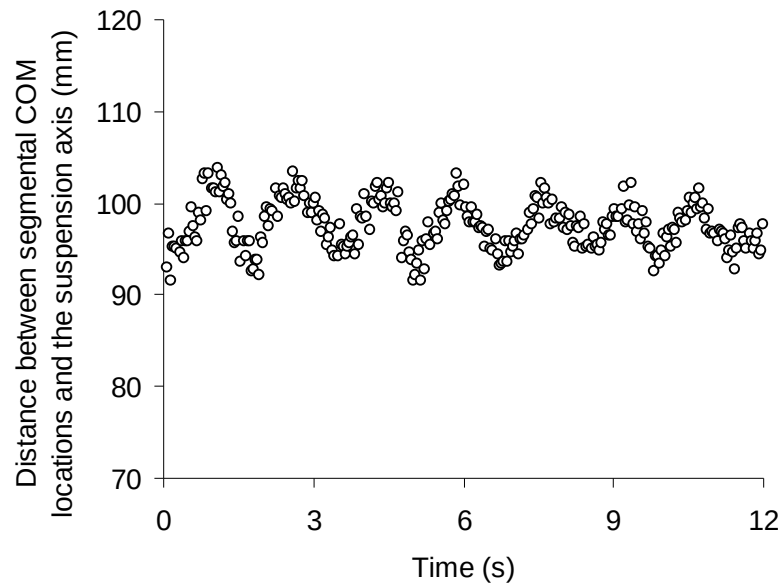


Figure 5. The distance between kinematic COM location (Zatsiorsky/De Leva model) and the suspension axis for the same subject shown in figure 4 over the same 12 second data collection period.

The mean difference between segmental kinematic COM location estimations and the direct suspension axis measurements over the 12 second measurement period ranged from 49mm to 110mm (mean 92 ± 17 mm) for the ZTDL model and 14mm to 55mm (mean 31 ± 13 mm) for the for the DT model (models significantly different from one another $P < 0.0001$).

3.3. The relationship between kinematic COM estimation error and subject specific anthropometric characteristics

The estimated error for either segmental kinematic model was not correlated to adiposity (body fat percentage, figure 6). The estimated error for the segmental kinematic models was also not related to the body mass (figure 7) and percentage body water (figure 8).

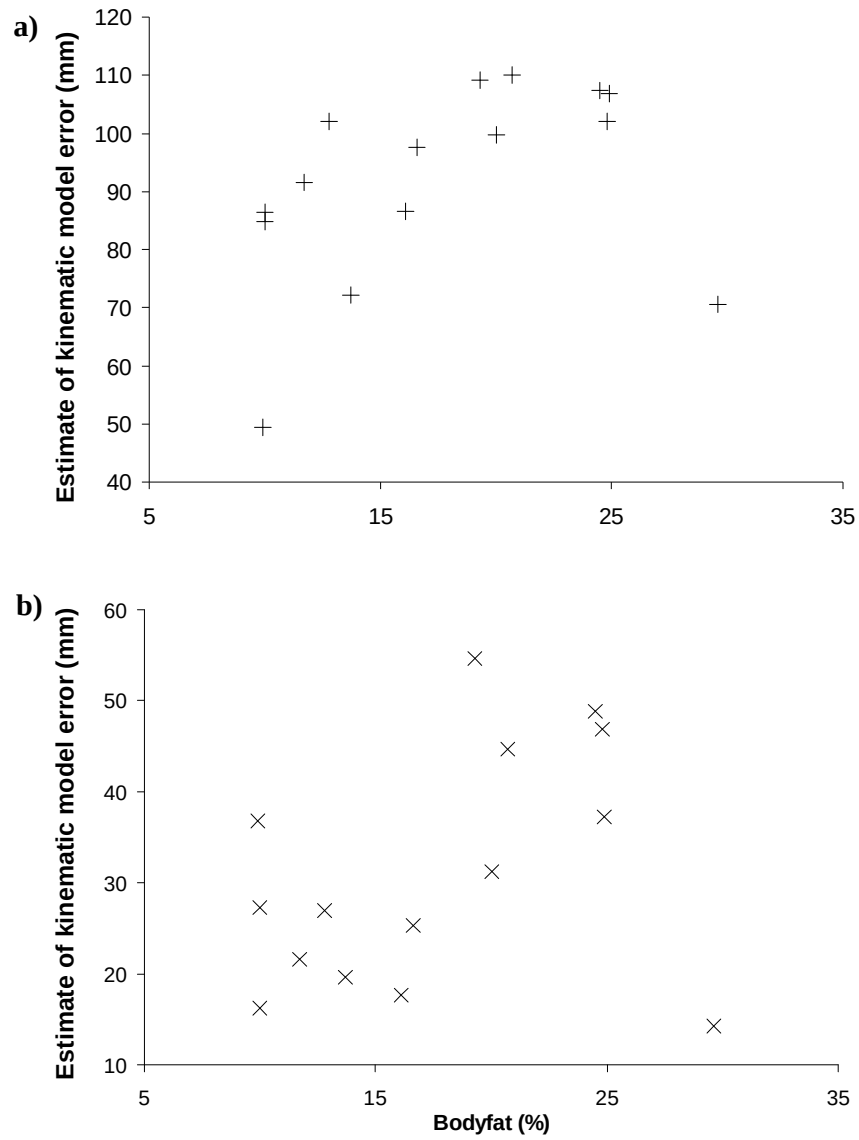


Figure 6. The relationship between mean distance between segmental kinematic COM location estimates and the suspension axis for each subject (an approximation of the error of COM location estimation) and adiposity (body fat percentage). Relationships are shown for both De Leva/Zatsiorsky (a) and Dempster (b) models. No significant relationship was found for either model ($R^2 < 0.15$).

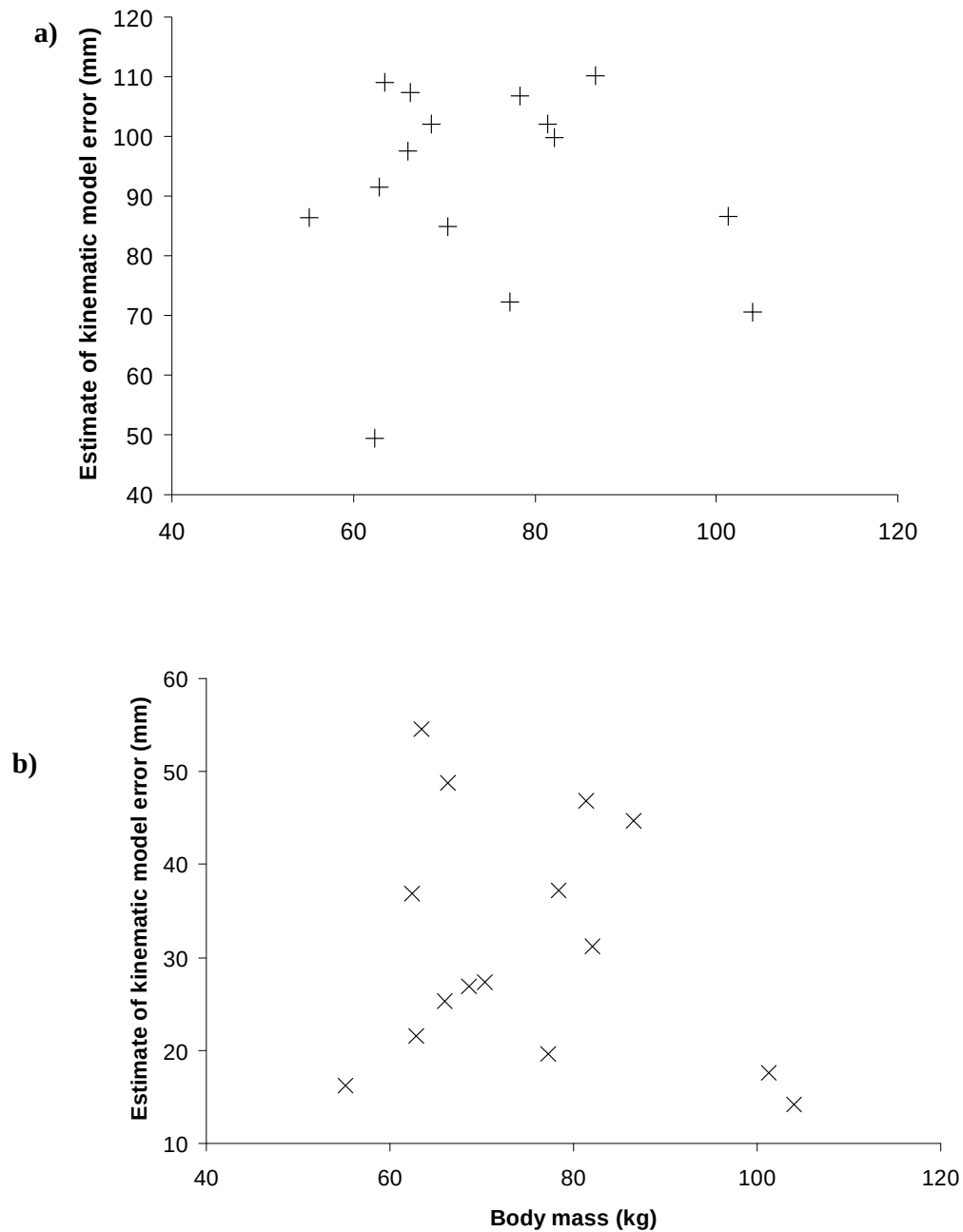


Figure 7. The relationship between mean distance between segmental kinematic COM location estimates and suspension axis for each subject (an approximation of the error of COM location estimation) and body mass. Relationships are shown for both De Leva/Zatsiorsky (a) and Dempster (b) models. No significant relationship was found for either model ($R^2 < 0.005$).

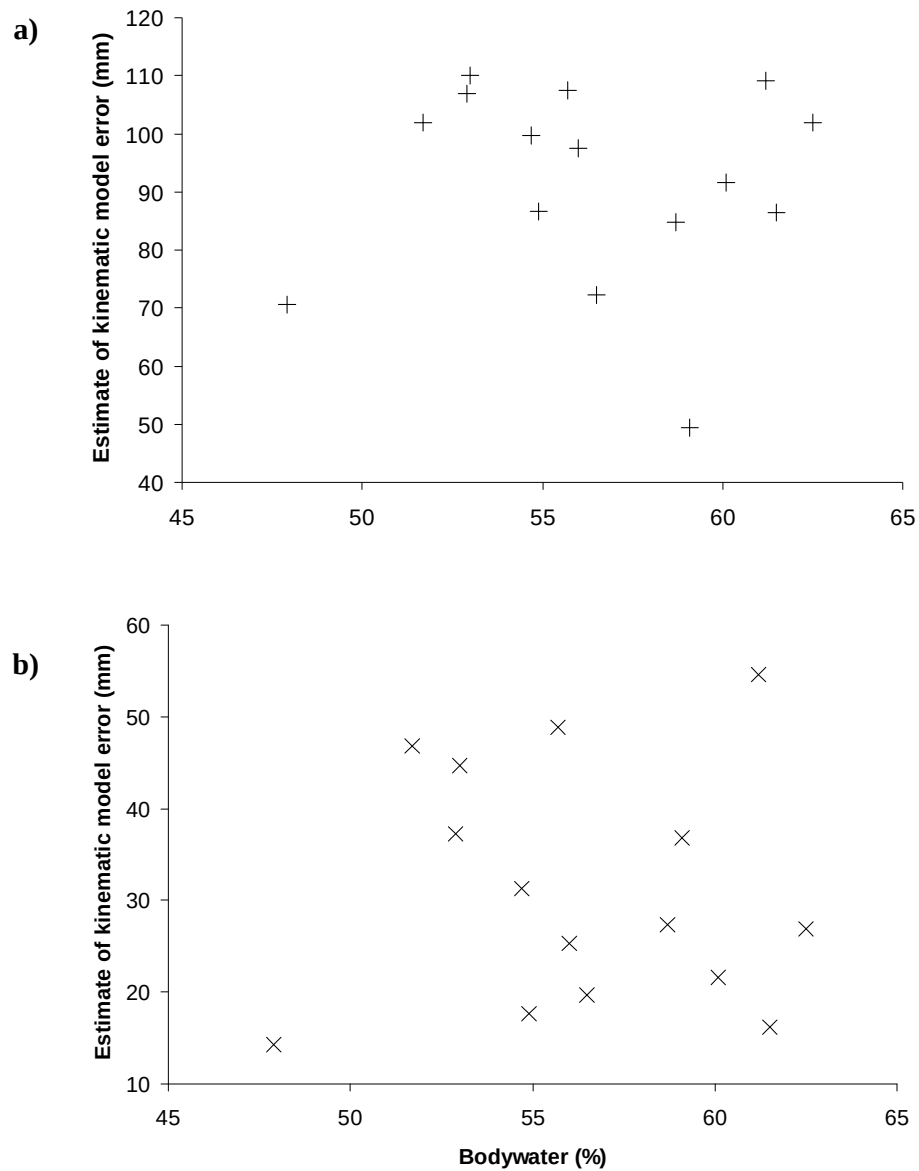


Figure 8. The relationship between mean distance between segmental kinematic COM location estimates and suspension axis for each subject (an approximation of the error of COM location estimation) and percentage body water. No significant relationship was found ($R^2 < 0.001$). Relationships are shown for both De Leva/Zatsiorsky (a) and Dempster (b) models. No significant relationship was found for either model ($R^2 < 0.001$).

4. Discussion

4.1 Kinematic models of COM location estimation

Kinematic estimation of COM location requires both modelling of joint centres and properties of body segments (specifically, mass and position of segments' centre of mass). The algorithm used in our study to identify joint centres and synthesise the 14 segment kinematic representation [40, 71] of our subjects is effective for both diagnostic [71] and scientific purposes [70, 110]. Similar algorithms are useful in defining COM locations for understanding age-related instability [72, 73, 94] and gait in persons with myelomeningocele [101].

After segment location determination, various models to approximate the proportional mass and locations of centres of mass of specific body segments, may be used to estimate whole body COM location. These were first derived from direct measurements performed on dismembered cadaver segments (such as Braune and Fischer 1889 and Dempster 1955), which display high theoretical accuracy (since direct measurements are made upon the individual segments), however they suffer from not being representative of live tissue, a concern that has shifted emphasis towards measurements on live humans [117]. To become more representative of live humans rather than frozen cadavers Zatsiorsky and Seluyanov [155] used a gamma scanning technique to locate segment boundaries and estimate densities, masses and segment centre of mass locations.

4.2 Choice of direct benchmark comparator: suspension axis measurements

Candidate comparator methods for benchmarking may include balancing techniques [17], suspension methods [19], reaction-board methods [124], see-saw methods [43],

ground reaction force methods [55], pendulum methods [135], alternative simplified kinematic methods such as sacral marker and pelvis reconstruction methods [126], and the standing-tipping method [19].

Excluding methods which themselves alter the morphology of a subject, are intentionally coarse methods, or those subject to secondary sources of error (specifically errors innate to force measurements), only three methods remain. These (balancing, suspension, and the see-saw method), are advantageous in being directly physics based and with no intermediate sensors, but application of these methods is arduous. Balancing and manual see-saw methods are particularly fraught with, possibly insurmountable, methodological difficulties because subjects need to be fully motionless. This cannot be achieved in live humans due to movement of quasirigid body components, inherent involuntary muscle movement including respiratory, cardio-ballistic and involuntary skeletal postural muscle activity.

As 1889 Braune and Fischer selected the suspension method as a reference standard for their segmental method, to take advantage of its theoretical accuracy and fewer associated problems. Similarly, and because the segmental method was founded on the premise of being similar to suspension, our study selected a suspension method as the primary reference standard. However, to define the suspension axis in this study, kinematic measurements of the two points defining the measurement axis were necessary. Such kinematic measurements are exposed to forms of error. Secondly, the suspension measurements in this study required subjects to remain near-motionless in a suspended position, which resulted in some degree of discomfort and occasional subject movement. To lessen the influence of subject discomfort (and the resulting

movement) we limited our subject to one seated position and to 12 seconds of data collection. The distance between modelled COM locations and the suspension axis varied over time (figures 4 and 5), primarily due to the skeletal muscle contractions employed by the subjects to remain still. To minimise potential effects due to subject movement, an average of 300 measurements of the distance between the suspension axis and the modelled COM was calculated.

The direct suspension method allows two dimensional COM localisation only (in a plane perpendicular to the suspension axis). Thus the actual three dimensional distance between a kinematically modelled COM point and a direct measurement of the COM point cannot be compared. Rather the perpendicular distance from the suspension axis and modelled COM point was used as the comparator variable. This is the only objective measurement of concordance between modelled and direct measured COM locations, and will be equal to or an overestimate of actual concordance between techniques.

4.3. Differences found between direct suspension measurements and kinematic estimates

Reasons for the significant differences between kinematic models and the direct suspension axis may include: errors inherent to each kinematic data set (inability of each model to adequately mirror the segmental properties of the subject under study), inability of the marker set to predict joint centre locations (including errors in marker placement and marker movement due to the movement of skin) [29], errors of image capture, processing and three dimensional reconstruction (in the current study the authors quantified this to be $\pm 6\text{mm}$ error) [120, 125], differences in determining the

locations of segment centres of mass and segments themselves (the borders of segments when the body is in different orientations) [154].

To explain the greater error displayed by the ZTDL model compared to the DT model we speculate that our subjects may have had somatotypes more reflective of the somatotypes of the cadavers in the Dempster study. If so, this is unlikely to be due to whole body mass similarities (see section 4.4 below) but to differences in mass distribution in each body segment. Secondly, Dempster (1955) measured the inertial parameters of cadaver segments directly (using balancing and suspension methods). Such direct measurements of both segment masses and COM locations are only possible in rigid (frozen) and individual (dismembered) body segments. Conversely, the ZTDL model is an indirect measurement which could be influenced accordingly.

In addition it should be noted that one particular candidate variable that is likely to heavily influence the accuracy of either segmental model, is the ability of these models to correctly identify the location of the trunk COM. Estimation of the trunk COM is prone to error when the assumption that the trunk body segment is comprised of either one or two rigid parts is made. Since the spine affords the trunk far greater movement than a simpler one or two segment model can account for, the estimation of trunk COM location using these simple models is likely to be prone to error. Additionally, because the trunk can comprise approximately 60% of the whole body mass, the magnitude of error in estimating the trunk COM, has a large influence on whole body COM determination.

4.4. Investigation of selected candidate variables for explaining differences between suspension and kinematic COM estimates

To investigate whether bias due to differences in body mass existed, we tested whether differences between suspension axis and kinematic model COM calculation (error) were correlated to body mass. The lack of correlation (figure 7) suggests that such bias is not readily evident. Note that we did not explore the relationship between segment specific mass distribution and kinematic COM error, which may still contribute to error.

Measurement of segment centre of mass locations for both the original DT and ZTDL models were made in supine body positions (the ZTDL data having been derived from both supine and upright body orientations). Kinematic models however are very rarely applied to purely supine subjects. It is possible that segment COM locations change when the orientation of body segments change. Two body components that would likely move when body orientation is changed due to their fluidity include body fat and body water. We therefore reasoned that subjects displaying greater amounts of the fluid body components would display a greater error of COM location determination. No such correlation was found between either body fat and body water and error estimation (figures 6, 8) for either kinematic model.

5. Conclusions

Scientific understanding of human movement and better understanding of gait pathology depend on accurate COM measurements. Our data demonstrate that in a suspended body position the COM locations of both cadaver-derived and live human-derived kinematic models differ from simultaneous direct measurement of COM

location. The cadaver-based kinematic model was significantly more closely related to the direct measurement than the live human-derived kinematic model; this may be due to the more direct methods used in the detection of segment specific centres of mass in cadavers. Basic analyses did not demonstrate the error in either kinematic model to be attributable to whole body mass, fat or water in our subjects. Additional research to understand these differences will facilitate improvements in the accuracy of kinematic estimations of COM location, an important biomechanical tool in several applied realms for which kinematic measurement techniques are in widespread use and uniquely offering three dimensional COM location capabilities, applicability to diverse environments and suitability to all human actions. One candidate factor that may likely show promise as a candidate variable for improving segmental method COM modelling is the identification of the trunk COM location.

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Chapter 6

Conclusions, Limitations and Future Research

6.1. Conclusions

As described in chapter 2 of this thesis, the many applications of COM location rely on the accuracy with which measurement techniques are able to estimate the location of the human COM. Of all the techniques available to measure COM location, the segmental method is currently the most popular. This popularity arises largely because of the kinematic segmental method's capacity for real-time data collection which does not rely on the presumption of qualities of the movement of COM, its ability to be used for many human body positions, movements and environments and its ability to estimate COM locations (rather than displacement only) in three dimensions. The accuracy with which this technique is able to quantify COM location in relation to direct measurements however, has seldom been tested, and the measurement uncertainty has never been tested in the many body positions for which it is commonly used today. Therefore this thesis' broad aim was to further knowledge of the uncertainty of COM measurements, knowledge which is vital to COM measurement applications such as in the clinical and sports domains.

In the past, direct measurement of COM location has been made using reaction-board techniques, which were assumed to be accurate (able to reflect 'true' values). In chapters 3 and 4 of this thesis, a reaction-board technique for the direct measurement of COM location was developed using the identical principles of force vector mathematics of previous reaction-boards, but with the advantage of being able to place subjects into body positions that mirror ambulation. Upon testing the accuracy of this reaction-board against an even more direct method for quantifying COM location (balancing), it was found that the assumption that a reaction-board is entirely accurate is invalid (reaction-board measurements do not reflect a benchmark standard

measurement technique). Such a finding is consistent with the GUM metrological approach and inconsistent with previous studies that have assumed that reaction-board measurements reflect 'true values'. The research contained in this thesis quantified the reaction-board system's inherent error to be maxima of 1.95cm and 2.42 cm for COM positions and displacements respectively.

Having quantified the accuracy of the reaction-board technique, this method was used as a secondary benchmark standard method (quantified measurement uncertainty) to evaluate the accuracy of the segmental technique (in the context of the reaction-board's own measurement uncertainty).

It was found that the mean difference between reaction-board and segmental measurements is as small as 1.6cm but that significant differences between COM locations determined by the two techniques exist. The two methods agree to within limits of 6.0 cm for single measurements on recumbent subjects positioned in a variety of stationary body positions. The agreement between the measurement methods appears to be similar irrespective of whether or not recumbent data are extrapolated to upright body positions (experiment 2 of chapter 4) or if such an extrapolation is not made (experiment 1 of chapter 4).

The research described in chapter 4 is the first to quantify the accuracy with which segmental method based techniques are able to measure COM locations and COM movement when applied to running subjects. The magnitude of differences determined from the research performed for this thesis was found to be larger than those reported by Braune and Fischer (1889). This could be due to the greater sample

size, number of body positions tested, and the use of live subjects in this thesis's studies, as opposed to the single cadaver used in the 1889 study. In contrast the more recent measurements of Davis (1973) fall within the range of accuracy shown in chapter 4, although Davis' research differed from this thesis in that it only measured three arbitrary body positions in two subjects.

The studies from chapter 4 have also contributed to the more modern GUM (the International Standards Organization Guide to the Expression of Uncertainty in Measurement) based approaches to measurement in that they have: quantified the repeatability of both a direct reaction-board and kinematic segmental COM location determination technique; established that the measurement uncertainty of the kinematic segmental method may vary under certain circumstances, with body orientation (both in respect of recumbancy assumptions and body aspect); and lastly estimated the overall measurement uncertainty of the kinematic segmental method, when a reaction-board standard comparator technique is used, as is described in the paragraph above.

The measurements which precede chapter 5 are all conducted using two dimensional direct and kinematic methods for determining COM location. Modern kinematic systems however estimate COM in three dimensions. The study in chapter 5 therefore used three-dimensional analysis techniques to quantify kinematic segmental estimates of COM location and did so using two different kinematic models. The standard benchmark comparator technique used in this study differs from the reaction-board method in the preceding studies. Rather, a suspension system, akin to the suspension system used to originally establish kinematic segmental COM estimation was built

and used. The direct suspension technique was employed in order to: i) escape the innate inaccuracy of the reaction-board method; ii) to allow the direct suspension and kinematic segmental methods to be compared simultaneously; iii) to be more suited to three-dimensional analysis; and iv) to be comparable to originating work establishing the kinematic segmental method.

Data from our comparisons between simultaneous direct suspension and kinematic segmental measurement of COM locations showed once again that significant differences exist between kinematically modelled COM locations and direct measurements. In addition it was found that a kinematic model derived from cadaver-based measurements was significantly more closely related to the direct measurement than a live human-derived kinematic model; this may be due to the more direct methods used in the detection of segment specific centres of mass in cadavers. To assess the nature of differences between the kinetic and direct measurement approaches, the relationship between error of measurement in these models and selected anthropometric variables was investigated. No correlation between error, and body mass, body water or adiposity was found.

The studies from chapter 5 have also contributed to the more modern GUM based metrological approaches in that they have: quantified the overall measurement uncertainty of kinematic methods when comparing these to a three dimensional suspension standard. Data from chapter 5 also compare the measurement uncertainty derived from two different kinematic models, finding that those a kinematic model derived from direct measurement of segmental inertial parameters on cadavers display less measurement uncertainty than a live human derived model. The measurement

uncertainty from either model was further found to be unrelated to candidate anthropometric variables.

In conclusion, novel reaction board and direct suspension apparatuses were purpose-built to allow direct measurements of COM location. The apparatus' accuracies were determined and three studies successfully conducted direct measurements of the location of human COM in walking, running, sitting and various recumbent body positions. Comparisons between direct COM location measurement and other less direct approaches allowed for the exploration of potential measurement uncertainty of popular indirect COM location determination techniques. Studies described here showed that significant differences exist between kinematically modelled COM locations and direct measurements and do so with a magnitude greater than what was reported in the original study that founded the segmental method of estimating COM location (Braune and Fischer 1889). This knowledge is critical to understanding the uncertainty of measurement and the GUM traceably chain for kinematic segmental models, which in turn are vital to COM measurement applications such as in the clinical and sports realms. The data presented in this thesis will hopefully facilitate improvements in the accuracy of kinematic estimations of COM location, a biomechanical tool with ever increasing applicability in many applied fields.

6.2. Potential limitations of this research

The first two studies of this thesis (chapters 3 and 4) yielded two dimensional analyses by using single camera images to estimate COM locations through the kinematic segmental approach. Although direct measurements can only be made in two dimensions, currently COM location measurements are most often conducted

using a three dimensional, optical tracking multi-camera system. Although three dimensional segmental methods are based on the same principles as the data reported in chapters 3 and 4's studies, the repetition of a similar study between some novel direct measurement method (for example, modified from the technique used in chapter 5 of this thesis) and the three-dimensionally kinematic segmental models, could more accurately describe the inaccuracy of the segmental methods. This may allow for the identification of correction factors to ultimately improve kinematic methods.

Despite the time-consuming nature of COM location measurements when made by a reaction-board method, error inherent to the reaction-board system is still evident. In contrast, the direct suspension measuring method of COM location theoretically offers the most accurate COM reference, but is typically only possible in one body position (sitting). The design of direct suspension harnesses which could facilitate a greater variety of body positions would allow for a more holistic investigation into kinematic segmental method measurement uncertainty.

One limitation of both the reaction-board and direct suspension measurement methods, is that both these methods require far more time, care, and physical unease of subjects for measurements to be made. For this reason it is unlikely that these methods will become routine in biomechanics laboratories, but may be used in a limited number of laboratories whose interest is concerned with measurement uncertainty of COM derived data.

The metrological approaches used in the studies described in this thesis may have been more systematically applied if the GUM (International Standards Organization Guide to the Expression of Uncertainty in Measurement) based approaches were more systematically implemented. Such considerations are not yet conventionally used in human biomechanics but it is likely that such an approach would ultimately lead to identification of all inherent error of segmental COM location estimation and the eventual refinement of such techniques, making the error (measurement uncertainty) magnitude negligible.

Examples where a GUM based approach could have been used to further the understanding of the measurement uncertainty found in chapters 4 and 5 of this thesis would have been to look at the influence of skin based marker placement and movement error as well as marker tracking errors and other computerized algorithm based error. Such studies could have compared different techniques (marker placement or computerized algorithms) against one another or assessed the stability of such methods over time.

6.3. Further research

The potential inaccuracy of the segmental method, which has been shown in the studies of this thesis (in particular chapters 4 and 5), are likely due to the modeling assumptions of the segmental method. One area of particular importance may be the modeling of the thorax, which, because of its large mass, can contribute approximately 60% of the total body mass. Current models used for COM location estimation assume this mass to be comprised of one or two rigid parts, which because of the highly flexible spine, is likely to be an inappropriate assumption. Testing the

influence of different models of the trunk (when built into a COM model), would therefore be a likely source of improvement of COM modeling accuracy and is recommended as a candidate for further research.

The novel reaction-board technique to measure COM location and movement presented in the first two studies of this thesis has the advantage of being less time-consuming and more accommodating of the assessment of varied body positions than the more direct balancing and suspension methods. As for many of the more direct measurement methods, this technique has a definable accuracy which allows for comparisons with less direct methods. The direct suspension method used in chapter 5, displays greater accuracy than the reaction-board technique, but is limited to fewer body positions. The kinematic segmental method is used to estimate COM locations in a wide variety of body types and a myriad of body positions. Repetition of the methodologies employed in Chapters 3,4 and 5, making use of the more direct COM location apparatus (reaction board or direct suspension harness), for example to include several more body positions, would better inform us of the accuracy with which the segmental method estimates COM locations in all its various applications. Another immediate approach to such study may be the identification of other anthropometric variables which could be tested as contributors to kinematic modeling error. It would be advisable for such studies to investigate both whole body and body segment specific morphologies. In addition, such studies may also investigate whether types of relationships other than linear relationships (as tested in chapter 5 of this thesis) exist, between the ‘measurement error’ of the segmental method and the magnitude of a candidate anthropometric variable.

Since at present the degree to which methods to estimate integration constants for force platform methods of measurement of COM movement are essentially theoretically based, the effect of different methods of estimating integration constants could be directly evaluated using comparisons between direct COM measurement (most likely using the reaction-board approach), the segmental kinematic method, and ground reaction force approaches.

An additional consequence of the data presented here is that more complex models may be devised to account for the errors seen between direct measurements of COM locations and segmental estimates. New adjustment algorithms could be developed using direct measurement methods, to enhance the accuracy of the segmental technique. In particular, studies that continue the work of this thesis, should make use of the most recent GUM (International Standards Organization Guide to the Expression of Uncertainty in Measurement -*due to be published in 2006, but not yet available at the time of submission of this thesis*) based approaches. Such approaches would allow for the identification of the most important contributors to the inaccuracy (measurement uncertainty) of these measurements and also elucidate how such sources of errors (measurement uncertainty) are linked, are propagated and contribute to overall inaccuracy, so that suitable refinement of kinematic models could be made.

Appendices

Appendix 1. Published definitions of both centre of mass and / or gravity.

Authors	Definition
Dawson 1935	“The force of gravity acts upon all parts of a body. But the effect is as if it acted upon a single point of the body with a force equal to the sum of the gravitational forces, each of which acts upon one of the particles of which the body is composed. If the body was suspended at this point it would be in perfect equilibrium no matter how much or in what direction it may be rotated about this point. This point is known as the ‘centre of gravity’ and the line which is determined by it and the centre of gravity of the earth is the ‘gravity line’ or ‘weight line’.”
Cooper and Glassow 1976	“Within every mass is a point about which the gravitational forces on one side are equal to those on the other. This balanced point, determined in three planes of the mass, is the centre of gravity.”
Johnson 1977	“The centre of mass of any given body, or system of bodies, is a point such that if any plane is passed through it, the mass moments on one side of the plane are equal to the mass moments on the other.”
Gowitzke and Milner	“The centre of gravity is the point in or about the body

1984	through which the resultant body force will act due to the gravitational pull of the earth (or over environment) upon the masses of the various body parts. The location of the centre of gravity changes as the limbs vary their relative positions.”
Benda <i>et al</i> 1994	“The centre of gravity is the point at which the total body mass can be assumed to be concentrated without altering the body’s translational inertia properties.”
Hamill and Knutzen 1995	“The body weight vector originates at a point referred to as the centre of gravity, or point about which all particles of the body of evenly distribute. The point about which the body’s mass is evenly distributed is referred to as the centre of mass.”
Kingma <i>et al</i> 1995	“When translation motions of the human body are studied, the entire mass of the body can be considered as concentrated in the centre of mass.”
Nichols <i>et al</i> 1995	“The centre of gravity refers to a point in the body at which the total force of gravity is considered to act and that is projected vertically onto the support surface.”
Luttgens and Hamilton 1997	“The centre of gravity of the body is sometimes described as its balance point or that point about which a body would balance without a tendency to rotate.”
Serway <i>et al</i> 2000	“The force of gravity exerted on an object can be

considered as acting at a single point called the centre of gravity. The centre of gravity of an object coincides with its centre of mass if the object is in a uniform field.”

Giancoli 2000

“Observations of the motion of bodies indicate that even if a body rotates, or there are several bodies that move relative to one another, there is one point that moves in the same path that a particle would if subjected to the same force. This point is called the centre of mass. The general motion of an extended body (or system of bodies) can be considered as the sum of the translational motion of the centre of mass, plus rotational, vibrational, or other types of motion about the centre of mass.” ... “A concept similar to centre of mass is centre of gravity. The centre of gravity of a body is that point at which the force of gravity can be considered to act.”

Appendix 2.1 Algorithm for marker tracking GUI based utility

```

function varargout = warxutility(varargin)
% This Algorithm generates a GUI for the manual and automated tracking of kinematic markers
%Authors: Trevor Ransome and Warrick McKinon
% Date: April 2006

% WARXUTILITY M-file for warxutility.fig
% WARXUTILITY, by itself, creates a new WARXUTILITY or raises the existing
% singleton*.
%
% H = WARXUTILITY returns the handle to a new WARXUTILITY or the handle to
% the existing singleton*.
%
% WARXUTILITY('CALLBACK',hObject,eventData,handles,...) calls the local
% function named CALLBACK in WARXUTILITY.M with the given input arguments.
%
% WARXUTILITY('Property','Value',...) creates a new WARXUTILITY or raises the
% existing singleton*. Starting from the left, property value pairs are
% applied to the GUI before warxutility_OpeningFunction gets called. An
% unrecognized property name or invalid value makes property application
% stop. All inputs are passed to warxutility_OpeningFcn via varargin.
%
% *See GUI Options on GUIDE's Tools menu. Choose "GUI allows only one
% instance to run (singleton)".
%
% Edit the above text to modify the response to help warxutility
% See also: GUIDE, GUIDATA, GUIHANDLES
% Last Modified by GUIDE v2.5 03-Apr-2006 16:28:24

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name', mfilename, ...
    'gui_Singleton', gui_Singleton, ...
    'gui_OpeningFcn', @warxutility_OpeningFcn, ...
    'gui_OutputFcn', @warxutility_OutputFcn, ...
    'gui_LayoutFcn', [] , ...
    'gui_Callback', []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before warxutility is made visible.
function warxutility_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject handle to figure
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
% varargin command line arguments to warxutility (see VARARGIN)

% Choose default command line output for warxutility

handles.output = hObject;
handles.prevSizes = 0;
handles.prevFrame = 0;
handles.edit = 0;
handles.ediplt = 0;
handles.minthreshval = 0;
handles.maxthreshval = 0;
handles.minsizeval = 0;
handles.maxsizeval = 0;
handles.trackpts = 0;
handles.noPointsChecked = 0;
handles.noPointsSelected = 0;
handles.point1 = 0;
handles.point2 = 0;
handles.point3 = 0;
handles.point4 = 0;
handles.point5 = 0;
handles.point6 = 0;
handles.point7 = 0;
handles.point8 = 0;
handles.point9 = 0;
handles.point10 = 0;
handles.point11 = 0;
handles.point12 = 0;
handles.point13 = 0;
handles.point14 = 0;
handles.point15 = 0;
handles.point16 = 0;
handles.point17 = 0;
handles.point18 = 0;
handles.point19 = 0;
handles.point20 = 0;
handles.point21 = 0;
handles.point22 = 0;
handles.point23 = 0;
handles.point24 = 0;
handles.point25 = 0;
handles.point26 = 0;
handles.point27 = 0;
handles.point28 = 0;
handles.point29 = 0;
handles.point30 = 0;
handles.point31 = 0;
handles.point32 = 0;
handles.point33 = 0;
handles.point34 = 0;
handles.point35 = 0;
handles.point36 = 0;
handles.point37 = 0;
handles.point38 = 0;
handles.point39 = 0;
handles.point40 = 0;
handles.point41 = 0;
handles.point42 = 0;

```

```

handles.point43=0;
handles.point44=0;
handles.point45=0;
handles.point46=0;
handles.point47=0;
handles.point48=0;
handles.point49=0;
handles.point50=0;
handles.point51=0;
handles.point52=0;
handles.point53=0;
handles.point54=0;
handles.point55=0;
handles.point56=0;
handles.point57=0;
handles.point58=0;
handles.point59=0;
handles.point60=0;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes warxutility wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = warxutility_OutputFcn(hObject, eventdata, handles)
% varargout cell array for returning output args (see VARARGOUT);
% hObject handle to figure
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;
%pos=get(handles.axes1,'position');
setappdata(handles.minthreshval, minthresh',0);
setappdata(handles.minsizeeval, 'minsize',0);
setappdata(handles.prevFrame, 'prevFrame',1);
setappdata(handles.maxsizeeval, 'maxsize',100);
setappdata(handles.prevSizes, 'prevSizes',0);
setappdata(handles.noPointsSelected, 'pointSelect',0);
setappdata(handles.trackpts, 'trackpts',0);
setappdata(handles.edit, 'editflag',0);
%set all prev point data to 0
for i=1:60
    str1=strcat('handles.point',int2str(i));
    str2=strcat('point',int2str(i));
    setappdata(eval(str1),str2,0);
end

% --- Executes on slider movement.
function thresholdslider1_Callback(hObject, eventdata, handles)
% hObject handle to thresholdslider1 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'Value') returns position of slider
% get(hObject,'Min') and get(hObject,'Max') to determine range of slider
threshmax=get(hObject,'Max');
threshmin=get(hObject,'Min');
thresh=get(hObject,'Value');
data=evalin('base','data');
frameNo=str2double(get(handles.txframeNo,'String'));
immax=max(max(data(:,:,1,frameNo)));
immin=min(min(data(:,:,1,frameNo)));
iminten=(immax-immin)*thresh+immin;

pos=[0.1200 0.09000 0.60 0.7450];

%check if prev fig drawn
fig1 = findobj('Tag','Fig1');
if ~isempty(fig1)
    delete(fig1)
end

%get(h, 'Position')
%axes('Position',pos);
%axes('Position',pos);
frameNo=str2double(get(handles.txframeNo,'String'));

lastframe=length(data(1,1,1,:));
if (frameNo <= lastframe)&(frameNo > 0)
    axes('Position',pos);
    intemp=double(data(:,:,1,frameNo));
    imdata=intemp.*(intemp>=iminten);
    imdata(imdata==0)=immin;
    imdata=uint8(imdata);
    h=subimage(imdata);
    a1 = get(h,'Parent');
    colormap hot;
    %turn xandy value display off
    set(a1,'Visible','off');
    %save image tag
    set(a1,'Tag','Fig1');
    %set button down event for point selection
    set(h,'ButtonDownFcn','warxutility(''fig1_ButtondownFcn'',gcbo,[],guidata(gcbo)))';
end;

setappdata(handles.thresh, thresh',iminten);

% --- Executes on button press in savemarkeraspushbutton.
function savemarkeraspushbutton_Callback(hObject, eventdata, handles)
% hObject handle to savemarkeraspushbutton (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
noPointsSelected=getappdata(handles.noPointsSelected, 'pointSelect');
filename=char(get(handles.savedataastextbox,'String'));
save(filename,noPointsSelected);
maxPtsinFrame=max(noPointsSelected);
for i=1:maxPtsinFrame
    str1=strcat('handles.point',int2str(i));
    str2=strcat('point',int2str(i));
    allpoints=getappdata(eval(str1),str2);
    eval(['point', int2str(i), '= allpoints']);
    save(filename,str2,'append');
end

% --- Executes on button press in playbutton.
function playbutton_Callback(hObject, eventdata, handles)
% hObject handle to playbutton (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB

```

```

% handles structure with handles and user data (see GUIDATA)
frameno = str2double(get(handles.txtframeno,'String'));
data=evalin('base','data');
set(handles.errormsg,'String','');
while (frameno < length(data(1,1,1:)))
    if strcmp(get(handles.errormsg,'String'),'')
        forwardbutton_Callback(eval('handles.forwardbutton'), eventdata, handles);
        frameno=frameno+1;
        pause(0.01);
    else
        return;
    end
end

% --- Executes on button press in pausebutton.
function pausebutton_Callback(hObject, eventdata, handles)
% hObject handle to pausebutton (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
set(handles.errormsg,'String','Paused');

% --- Executes on button press in OpenAVIButton.
function OpenAVIButton_Callback(hObject, eventdata, handles)
% hObject handle to OpenAVIButton (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

%delete existing frame display
%delete(handles.axes1);
%create new axes

%Open avi or mat file
set(handles.errormsg,'String','');
filename = get(handles.filename,'String');
imfound=false;
if filename(length(filename))=='\
%mat file
vars=load(filename);
names=fieldnames(vars);
for i=1:length(names)
    data=getfield(vars,char(names(i)));
    if (length(size(data))==4)&(isa(data,'uint8'))
        imfound=true;
        break;
    end
end;
if imfound
    assignin('base','data',data);
else
    str='No variable found of dimension = 4 and of type = uint8';
    set(handles.errormsg,'String',str);
    set(handles.errormsg,'Visible','on');
    return;
end;
% data=evalin('base','data');
else
end
width=length(data(:,1,1));
setappdata(handles.maxthreshval,'maxthresh',max(max(data(:,1,1))));

% %create image axes
% %pos=[-0.08 0.328 0.65 0.65];
% %
% pos=[0.1200 0.09000 0.60 0.7450];
% %pos=[29.8000 4.0331 108.0000 33.5458];
set(handles.txtframeno,'String',1);
%check if prev fig drawn
fig1 = findobj('Tag','Fig1');
if ~isempty(fig1)
    delete(fig1)
end
numPointsSelected=zeros(length(data(1,1,1:)),1);
setappdata(handles.noPointsSelected,'pointSelect',numPointsSelected);
axes('Position',pos);
%get(h,'Position')
%axes('Position',pos);
%axes('Position',pos);
h=subimage(data(:,1,1));
a1 = get(h,'Parent');

%turn xandy value display off
set(a1,'Visible','off');
%save image tag
set(a1,'Tag','Fig1');
%set button down event for point selection
set(h,'ButtonDownFcn','warxutility(''fig1_ButtondownFcn'',gcbo,[],guidata(gcbo)))

function varargout = fig1_ButtondownFcn(h, eventdata, handles, varargin)
% Stub for ButtondownFcn of the axes handles.axes1.

numPointsSelected = getappdata(handles.noPointsSelected,'pointSelect');
frameno=str2double(get(handles.txtframeno,'String'));
if (numPointsSelected(frameno) < 60)
    %check next
    editflag=getappdata(handles.edit,'editflag');
    if editflag==0
        numPointsSelected(frameno)=numPointsSelected(frameno)+1;
        str1=strcat(handles.point,int2str(numPointsSelected(frameno)));
        str2=strcat('point',int2str(numPointsSelected(frameno)));
        allpoints=getappdata(eval(str1),str2);
        setappdata(handles.noPointsSelected,'pointSelect',numPointsSelected);
        str3=strcat(handles.edit,int2str(numPointsSelected(frameno)));
        set(eval(str3),'Enable','on');
        str3=strcat(handles.showtrackbutton,int2str(numPointsSelected(frameno)));
        set(eval(str3),'Enable','on');
        figparent = findobj('Tag','Fig1');
        %get position of click event
        g=get(figparent,'CurrentPoint');
        point(1)=g(1);
        point(2)=g(3);
        %setappdata(eval(str1),str2,point);

        allpoints(frameno,1:2)=point;
        setappdata(eval(str1),str2,allpoints);
        hold on;
        h=plot(g(1),g(3),'r');
        set(h,'ButtonDownFcn','warxutility(''fig1_ButtondownFcn'',gcbo,[],guidata(gcbo)))
        if get(eval(str3),'Value')==1
            %get track colour
            colour=get(handles.trackcolour,'String');

```

```

        set(handles.trackprop,'String',colours(numPointsSelected(frameeno),:));
        showtrackbutton_Callback(eval(str3), eventdata, handles);
    end
    %check box
    str3=strcat(handles.checkbox',int2str(numPointsSelected(frameeno)));
    set(eval(str3),'Value',1);
else
    setappdata(handles.edit,'editflag',0);
    pointno=getappdata(handles.editpt,'editpt');
    str_edit=strcat(handles.edit',int2str(pointno));
    set(eval(str_edit),'Value',0);
    str1=strcat(handles.point',int2str(pointno));
    str2=strcat('point',int2str(pointno));
    allpoints=getappdata(eval(str1),str2);
    hold on
    h=plot(allpoints(frameeno,1),allpoints(frameeno,2),'k');
    set(h,ButtonDownFcn','warxutility("fig1_ButtondownFcn",gcbo,[1,guidata(gcbo)]));
    figparent = findobj('Tag','Fig1');
    %get position of click event
    g=get(figparent,'CurrentPoint');
    point(1)=g(1);
    point(2)=g(3);
    %setappdata(eval(str1),str2,point);

    allpoints(frameeno,1:2)=point;
    setappdata(eval(str1),str2,allpoints);
    hold on;
    h=plot(g(1),g(3),':');
    set(h,ButtonDownFcn','warxutility("fig1_ButtondownFcn",gcbo,[1,guidata(gcbo)]));
    str3=strcat(handles.showtrackbutton',int2str(numPointsSelected(frameeno)));
    if get(eval(str3),'Value')==1
        set(eval(str3),'Value',0);
        showtrackbutton_Callback(eval(str3), eventdata, handles);
        colours=get(handles.trackcolour,'String');
        set(handles.trackprop,'String',colours(numPointsSelected(frameeno),:));
        set(eval(str3),'Value',1);
        showtrackbutton_Callback(eval(str3), eventdata, handles);
    end
end
%set(eval(str3),'Enable','on');
%trackpts=getappdata(handles.trackpts,trackpts);
%trackpts(length(trackpts))=numPointsSelected;
%trackpts(length(trackpts)+1)=0;
%setappdata(handles.trackpts,trackpts,trackpts);
else
    msgbox('Maximum number of points have been selected','Error','error');
end

function plotpoints(handles,frameeno,eventdata)
%plots all points on frame
numPointsSelected = getappdata(handles.noPointsSelected,'pointSelect');
if (numPointsSelected(frameeno)>0)
    hold on
    for i = 1:numPointsSelected(frameeno)
        str1=strcat(handles.point',int2str(i));
        str2=strcat('point',int2str(i));
        allpoints=getappdata(eval(str1),str2);
        h=plot(allpoints(frameeno,1),allpoints(frameeno,2),':');
        set(h,ButtonDownFcn','warxutility("fig1_ButtondownFcn",gcbo,[1,guidata(gcbo)]));
        str1=strcat(handles.checkbox',int2str(i));
        set(eval(str1),'Value',1);
        str1=strcat(handles.edit',int2str(i));
        set(eval(str1),'Enable','on');
        str1=strcat(handles.showtrackbutton',int2str(i));
        set(eval(str1),'Enable','on');
        if get(eval(str1),'Value')==1
            %get track colour
            colours=get(handles.trackcolour,'String');
            set(handles.trackprop,'String',colours(numPointsSelected(frameeno),:));
            showtrackbutton_Callback(eval(str1), eventdata, handles);
        end
    end
end

function clearptlist(handles)
%clear all data in point list
frameeno=getappdata(handles.prevFrame,'prevFrame');
data=evalin('base','data');
if (frameeno>0)&&(frameeno<length(data(1,1,1:1))+1))
    numPointsSelected = getappdata(handles.noPointsSelected,'pointSelect');
    if (numPointsSelected(frameeno)>0)
        for i = 1:numPointsSelected(frameeno)
            str1=strcat(handles.checkbox',int2str(i));
            set(eval(str1),'Value',0);
            str1=strcat(handles.edit',int2str(i));
            set(eval(str1),'Enable','off');
            set(eval(str1),'Value',0);
            str1=strcat(handles.showtrackbutton',int2str(i));
            set(eval(str1),'Enable','off');
            %set(eval(str1),'Value',0);
        end
    end
end

% --- Executes on button press in startbtn.
function startbtn_Callback(hObject, eventdata, handles)
% hObject handle to startbtn (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
pos=[0.1200 0.09000 0.60 0.7450];
%pos=[29.8000 4.0331 108.0000 33.5458];

setappdata(handles.prevFrame,'prevFrame',1);

%check if prev fig drawn
fig1 = findobj('Tag','Fig1');
if ~isempty(fig1)
    delete(fig1)
end
axes('Position',pos);

data=evalin('base','data');
clearptlist(handles);
setappdata(handles.prevFrame,'prevFrame',1);
set(handles.txtframeeno,'String',1);
h=subimage(data(:,:,1,1));
a1 = get(h,'Parent');
%turn xandy value display off
set(a1,'Visible','off');
%save image tag
set(a1,'Tag','Fig1');

```

```

%set button down event for point selection
set(h,ButtonDownFcn,'warxutility(''fig1_ButtondownFcn'',gcbo,[],guidata(gcbo)));
plotpoints(handles,1,eventdata);

% --- Executes on button press in endbutton.
function endbutton_Callback(hObject, eventdata, handles)
% hObject    handle to endbutton (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
pos=[0.1200  0.09000  0.60  0.7450];
%pos=[29.8000  4.0331 108.0000  33.5458];

%check if prev fig drawn
fig1 = findobj('Tag','Fig1');
if ~isempty(fig1)
    delete(fig1)
end
axes('Position',pos);
%get(h,'Position')
%axes('Position',pos);
data=evalin('base','data');
lastframe=length(data(1,1,1,:));
clearptlist(handles);
setappdata(handles.prevFrame,'prevFrame',lastframe);
set(handles.txtframeono,'String',lastframe);
h=subimage(data(:,:,1,lastframe));
a1 = get(h,'Parent');
plotpoints(handles,lastframe,eventdata);
%turn xandy value display off
set(a1,'Visible','off');
%save image tag
set(a1,'Tag','Fig1');
%set button down event for point selection
set(h,ButtonDownFcn,'warxutility(''fig1_ButtondownFcn'',gcbo,[],guidata(gcbo)));

function result = checkLocality(pts,handles)
distcheck=str2double(get(handles.localitydist,'String'));
result =1;
for i=1:(length(pts(:,1))-1)
    for j=(i+1):(length(pts(:,1)))
        dist=sqrt((pts(i,1)-pts(j,1))^2+((pts(i,2)-pts(j,2))^2));
        if dist <= distcheck
            result =0;
            str='Found points fall within specified locality value';
            disp(str);
            set(handles.errormsg,'String',str);
            set(handles.errormsg,'Visible','on');
            beep;
            return;
        end
    end
end
end

% --- Executes on button press in forwardbutton.
function forwardbutton_Callback(hObject, eventdata, handles)
% hObject    handle to forwardbutton (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
set(handles.errormsg,'Visible','off');
set(handles.errormsg,'String','');
pos=[0.1200  0.09000  0.60  0.7450];
%pos=[29.8000  4.0331 108.0000  33.5458];

%check if prev fig drawn
fig1 = findobj('Tag','Fig1');
if ~isempty(fig1)
    delete(fig1)
end
end

%get(h,'Position')
%axes('Position',pos);
%axes('Position',pos);
data=evalin('base','data');
frameno=str2double(get(handles.txtframeono,'String'))+1;
clearptlist(handles);
setappdata(handles.prevFrame,'prevFrame',frameno);
set(handles.txtframeono,'String',int2str(frameno));
lastframe=length(data(1,1,1,:));
if (frameno <= lastframe)&(frameno > 0)
    axes('Position',pos);
    set(handles.txtframeono,'String',frameno);
    h=subimage(data(:,:,1,frameno));
    a1 = get(h,'Parent');
    numfoundpt=0;
    foundpt={0 0};
    %If not manualsearch
    if get(handles.manualsearch,'Value')==0
        numPointsSelected = getappdata(handles.noPointsSelected,'pointSelect');
        for i = 1:numPointsSelected(frameno-1)
            str1=strcat(handles.point',int2str(i));
            str2=strcat('point',int2str(i));
            allpoints=getappdata(eval(str1),str2);
            if length(allpoints(:,1))<frameno
                allpoints(frameno,1:2)=[0 0];
            end
            if (allpoints(frameno,1)==0)
                [pt,found]=getNearestPt(handles,double(data(:,:,1,frameno)),i);
                if found
                    numfoundpt=numfoundpt+1;
                    foundpt(numfoundpt,1:2)=pt;
                else
                    break;
                end
            end
        end
        %check all points found
        if (numfoundpt == numPointsSelected(frameno-1))&(checkLocality(foundpt,handles)==1)
            for i=1:numfoundpt
                str1=strcat(handles.point',int2str(i));
                str2=strcat('point',int2str(i));
                allpoints=getappdata(eval(str1),str2);
                allpoints(frameno,1)=foundpt(i,1);
                allpoints(frameno,2)=foundpt(i,2);
                setappdata(eval(str1),str2,allpoints);
                numPointsSelected(frameno)=numPointsSelected(frameno)+1;
                setappdata(handles.noPointsSelected,'pointSelect',numPointsSelected);
            end
        elseif numfoundpt ~= numPointsSelected(frameno-1)
            set(handles.manualsearch,'Value',1);
            set(handles.centsearch,'Value',0);
        end
    end
end

```

```

        set(handles.peaksearch,'Value',0);
        str='Not all points could be found';
        disp(str);
        set(handles.errormsg,'String',str);
        set(handles.errormsg,'Visible','on');
        beep;
    end
end
plotpoints(handles,frameno,eventdata);
%turn xandy value display off
set(a1,'Visible','off');
%save image tag
set(a1,'Tag','Fig1');
%set button down event for point selection
set(h,ButtonDownFcn,'warxutility("fig1_ButtondownFcn",gcbo,[],guidata(gcbo)))';
end;

% --- Executes on button press in backbutton.
function backbutton_Callback(hObject, eventdata, handles)
% hObject handle to backbutton (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
pos=[0.1200 0.09000 0.60 0.7450];
%pos=[29.8000 4.0331 108.0000 33.5458];

%check if prev fig drawn
fig1 = findobj('Tag','Fig1');
if ~isempty(fig1)
    delete(fig1)
end

%get(h,'Position')
%axes('Position',pos);
%axes('Position',pos);
data=evalin('base','data');
frameno=str2double(get(handles.txframeno,'String'))-1;
clearptlist(handles);
setappdata(handles,prevFrame,prevFrame,frameno);
set(handles.txframeno,'String',int2str(frameno));
lastframe=length(data(1,1,:));
if (frameno > 0)&(frameno <= lastframe)
    axes('Position',pos);
    set(handles.txframeno,'String',frameno);
    h=subimage(data(:,:,1,frameno));
    a1 = get(h,'Parent');
    plotpoints(handles,frameno,eventdata);
    %turn xandy value display off
    set(a1,'Visible','off');
    %save image tag
    set(a1,'Tag','Fig1');
    %set button down event for point selection
    set(h,ButtonDownFcn,'warxutility("fig1_ButtondownFcn",gcbo,[],guidata(gcbo)))';
end;

% --- Executes on button press in checkbox1.
% function checkbox_Callback(hObject, eventdata, handles)
% % hObject handle to checkbox1 (see GCBO)
% % eventdata reserved - to be defined in a future version of MATLAB
% % handles structure with handles and user data (see GUIDATA)
% % Hint: get(hObject,'Value') returns toggle state of checkbox1
% if get(hObject,'Value')==1
%     trackpts=getappdata(handles,trackpts,'trackpts');
%     checktag=get(hObject,'Tag');
%     checknum=checktag(9:length(checktag));
%     pointind=str2double(checknum);
%     trackpts(length(trackpts))=pointind;
%     trackpts(length(trackpts)+1)=0;
%     setappdata(handles,trackpts,'trackpts',trackpts);
% else
%     trackpts=getappdata(handles,trackpts,'trackpts');
%     checktag=get(hObject,'Tag');
%     checknum=checktag(9:length(checktag));
%     pointind=str2double(checknum);
%     ind=find(trackpts==pointind);
%     if ind==1
%         newpts=trackpts(2:length(trackpts));
%     else
%         newpts=trackpts(1:(ind-1));
%         newpts((ind):(length(trackpts)-1))=trackpts((ind+1):(length(trackpts)));
%     end
%     setappdata(handles,trackpts,'trackpts',newpts);
% end

% --- Executes on button press in edit1.
function edit_Callback(hObject, eventdata, handles)
% hObject handle to edit1 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of edit1
if get(hObject,'Value')==1
    radtag=get(hObject,'Tag');
    pointno=radtag(5:length(radtag));
    str1=strcat('handles.point',pointno);
    str2=strcat('point',pointno);
    points=getappdata(eval(str1),str2);
    frameno=get(handles.txframeno,'String');
    hold on
    h=plot(points(str2double(frameno),1),points(str2double(frameno),2),'b');
    set(h,ButtonDownFcn,'warxutility("fig1_ButtondownFcn",gcbo,[],guidata(gcbo)))';
    setappdata(handles.edit,'editflag',1);
    setappdata(handles.editpt,'str2double(pointno)');
else
    radtag=get(hObject,'Tag');
    pointno=radtag(5:length(radtag));
    str1=strcat('handles.point',pointno);
    str2=strcat('point',pointno);
    points=getappdata(eval(str1),str2);
    frameno=get(handles.txframeno,'String');
    hold on
    h=plot(points(str2double(frameno),1),points(str2double(frameno),2),'r');
    set(h,ButtonDownFcn,'warxutility("fig1_ButtondownFcn",gcbo,[],guidata(gcbo)))';
    setappdata(handles.edit,'editflag',0);
end

% --- Executes on button press in btnGotoFrame.
function btnGotoFrame_Callback(hObject, eventdata, handles)
% hObject handle to btnGotoFrame (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB

```

```

% handles    structure with handles and user data (see GUIDATA)
pos=[0.1200  0.09000  0.60  0.7450];
%pos=[29.8000  4.0331  108.0000  33.5458];

%check if prev fig drawn
fig1 = findobj('Tag','Fig1');
if ~isempty(fig1)
    delete(fig1)
end

%get(h,'Position')
%axes('Position',pos);
%axes('Position',pos);
data=evalin('base','data');
frameno=str2double(get(handles.txtframeno,'String'));
clearptlist(handles);
setappdata(handles,prevFrame,'prevFrame',frameno);
%set(handles.txtframeno,'String',int2str(frameno));
lastframe=length(data(1,1,1,:));
if (frameno > 0)&(frameno <= lastframe)
    axes('Position',pos);
    set(handles.txtframeno,'String',frameno);
    h=subimage(data(:,:,1,frameno));
    a1 = get(h,'Parent');
    plotpoints(handles,frameno,eventdata);
    %turn xandy value display off
    set(a1,'Visible','off');
    %save image tag
    set(a1,'Tag','Fig1');
    %set button down event for point selection
    set(h,'ButtonDownFcn',warxutility('fig1_ButtowndownFcn',gcbo,[],guidata(gcbo)));
end;

% --- Executes on button press in showtrackbutton1.
function showtrackbutton_Callback(hObject, eventdata, handles)
% hObject    handle to showtrackbutton1 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of showtrackbutton1
radiotag=get(hObject,'Tag');
pointno=str2double(radiotag(16:length(radiotag)));
if get(hObject,'Value')==1
    frameno=str2double(get(handles.txtframeno,'String'));
    str1=strcat('handles.point',int2str(pointno));
    str2=strcat('point',int2str(pointno));
    allpoints=getappdata(eval(str1),str2);

    ptx=0;
    pty=0;
    ptnum=1;
    for i=1:frameno
        if (allpoints(i,1)~=0)&(allpoints(i,2)~=0)
            ptx(ptnum)=allpoints(i,1);
            pty(ptnum)=allpoints(i,2);
            ptnum=ptnum+1;
        end
    end
    trackprop=get(handles.trackprop,'String');
    h=plot(ptx,pty,trackprop);
    set(h,'ButtonDownFcn',warxutility('fig1_ButtowndownFcn',gcbo,[],guidata(gcbo)));
    str1=strcat('TrackFig',int2str(pointno));
    set(h,'Tag',str1);
    colours=get(handles.trackcolour,'String');
    colours(pointno,1:length(trackprop))=trackprop;
    set(handles.trackcolour,'String',colours);
else
    str1=strcat('TrackFig',int2str(pointno));
    fig1 = findobj('Tag',str1);
    if ~isempty(fig1)
        delete(fig1);
    end
end

% --- Executes on slider movement.
function minthresh_Callback(hObject, eventdata, handles)
% hObject    handle to minthresh (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'Value') returns position of slider
%   get(hObject,'Min') and get(hObject,'Max') to determine range of slider
threshmax=get(hObject,'Max');
threshmin=get(hObject,'Min');
thresh=get(hObject,'Value');
data=evalin('base','data');
frameno=str2double(get(handles.txtframeno,'String'));
immax=max(max(data(:,:,1,frameno)));
immin=min(min(data(:,:,1,frameno)));
imMinInten=(immax-immin)*thresh+immin;
setappdata(handles.minthreshval,'minthresh',imMinInten);

function trackprop_CreateFcn(hObject, eventdata, handles)
% --- Executes on slider movement.
function maxthresh_Callback(hObject, eventdata, handles)
% hObject    handle to maxthresh (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'Value') returns position of slider
%   get(hObject,'Min') and get(hObject,'Max') to determine range of slider
threshmax=get(hObject,'Max');
threshmin=get(hObject,'Min');
thresh=get(hObject,'Value');
data=evalin('base','data');
frameno=str2double(get(handles.txtframeno,'String'));
immax=max(max(data(:,:,1,frameno)));
immin=min(min(data(:,:,1,frameno)));
imMaxInten=(immax-immin)*thresh+immin;
setappdata(handles.maxthreshval,'maxthresh',imMaxInten);

% --- Executes on slider movement.
function minsize_Callback(hObject, eventdata, handles)
% hObject    handle to minsize (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'Value') returns position of slider
%   get(hObject,'Min') and get(hObject,'Max') to determine range of slider
minsize=get(hObject,'Value');
setappdata(handles.minsizeval,'minsize',minsize);

```

```

% --- Executes on slider movement.
function maxsize_Callback(hObject, eventdata, handles)
% hObject handle to maxsize (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'Value') returns position of slider
% get(hObject,'Min') and get(hObject,'Max') to determine range of slider
maxsize=get(hObject,'Value');
setappdata(handles.maxsizeeval,'maxsize',maxsize);

function velocity_Callback(hObject, eventdata, handles)
% hObject handle to velocity (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of velocity as text
% str2double(get(hObject,'String')) returns contents of velocity as a double

% --- Executes on button press in applybtn.
function applybtn_Callback(hObject, eventdata, handles)
% hObject handle to applybtn (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
numPointsSelected = getappdata(handles.noPointsSelected,'pointSelect');
frameno=str2double(get(handles.txframeno,'String'));
if numPointsSelected(frameno) == 0
    str='No points on image selected to show local region.';
    disp(str);
    set(handles.errormsg,'String',str);
    set(handles.errormsg,'Visible','on');
    beep;
    return;
end
data=evalin('base','data');
velocity = str2double(get(handles.velocity,'String'));
figsize=[577.1621 720.6655];

for i=1:numPointsSelected(frameno)
    str1=strcat('handles.point',int2str(i));
    str2=strcat('point',int2str(i));
    allpoints=getappdata(eval(str1),str2);
    them=getRegion(data(:,1,frameno),allpoints(frameno,1:2),velocity,figsize);
    localim(1:length(them(:,1)),1:length(them(1,:)),i)=them;
end
%save to workspace
assignin('base','localim',localim);
if get(handles.localmanual,'Value')==0
    h = localthresh(-1);
else
    h = localthresh(get(handles.localthreshslider,'Value'));
end
if h ==-1
    set(handles.localmanual,'Value',0);
    set(handles.localthreshslider,'Enable','off');
elseif h ~=5
    set(handles.localmanual,'Value',1);
    set(handles.localthreshslider,'Enable','on');
    set(handles.localthreshslider,'Value',h);
end

% --- Executes on button press in manualthresh.
function manualthresh_Callback(hObject, eventdata, handles)
% hObject handle to manualthresh (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of manualthresh
if get(hObject,'Value')==1
    set(handles.minthresh,'Enable','on');
else
    set(handles.minthresh,'Enable','off');
end

function [newpt,found]=getNearestPt(handles,im,pointno)
newpt=0;
frameno=str2double(get(handles.txframeno,'String'));
str1=strcat('handles.point',int2str(pointno));
str2=strcat('point',int2str(pointno));
allpoints=getappdata(eval(str1),str2);
check=false;
found=false;
if (frameno>2)
    if (allpoints(frameno-1,1)~=0)&(allpoints(frameno-2,1)~=0)
        prevpt1=allpoints(frameno-2,1:2);
        prevpt2=allpoints(frameno-1,1:2);
        newGuessspt=2*prevpt2-prevpt1;
        check=true;
    else
        check=false;
    end
end
if (frameno>1)&(~check)
    if (allpoints(frameno-1,1)~=0)
        newGuessspt=allpoints(frameno-1,1:2);
    else
        return;
    end
elseif (~check)
    return;
end

velocity=str2double(get(handles.velocity,'String'));
figsize=[577.1621 720.6655];
if get(handles.globalthresh,'Value')==1
    if get(handles.manualthresh,'Value')==1
        thresh=get(handles.minthresh,'Value')*max(max(im));
    else%if get(handles.graythresh2,'Value')==1
        thresh=graythresh(im)*max(max(im));
    % else
    % thresh=gaussianthresh(im);
    end
    BW=im>thresh;
    BWRegion=getRegion(BW,newGuessspt,velocity,figsize);
    imglobal=BW.*im;
else
    imglobal=im;
end

```

```

end

%fig1 = findobj('Tag','Fig1');
imRegion=getRegion(imglobal,newGuesspt,velocity,figsize);

if get(handles.localthresh,'Value')==1
    if get(handles.localmanual,'Value')==1
        thresh=get(handles.localthreshslider,'Value')*max(max(imRegion));
    else%if get(handles.graythresh,'Value')==1
        thresh=graythresh(imRegion)*max(max(imRegion));
    % else
    %     thresh=gaussianthresh(imRegion);
    end
    BWRegion=imRegion>thresh;
    imRegion=BWRegion.*imRegion;
end

BWRegion=imclearborder(BWRegion,4);
%BWRegion=bwmorph(BWRegion,'bridge');
BWRegion=bwmorph(BWRegion,'clean');
BWRegion=bwmorph(BWRegion,'fill');
[BWSep,num] = bwlabel(BWRegion,4);
prevdist=velocity*2;

for n=1:num
    BWInd=BWSep==n;
    if get(handles.centsearch,'Value')==1
        Stats=regionprops(double(BWInd),'Centroid');
        thepoint=Stats.Centroid;
        dist=sqrt((velocity-thepoint(1))^2+(velocity-thepoint(2))^2);
        if dist < prevdist
            prevdist=dist;
            newpt(1)=newGuesspt(1)-velocity+thepoint(1);
            newpt(2)=newGuesspt(2)-velocity+thepoint(2);
            found=true;
        elseif dist == prevdist
            found=false;
        end
    elseif get(handles.peaksearch,'Value')==1
        imInd=BWInd.*imRegion;
        imInd=imfilter(imInd,ones(3,3));
        immax=max(max(imInd));
        BWInd=imInd==immax;
        Stats=regionprops(BWInd,'Centroid');
        thepoint=Stats.Centroid;
        dist=(velocity-thepoint(1))^2+(velocity-thepoint(2))^2;
        if dist < prevdist
            prevdist=dist;
            newpt(1)=newGuesspt(1)-velocity+thepoint(1);
            newpt(2)=newGuesspt(2)-velocity+thepoint(2);
            found=true;
        elseif dist == prevdist
            found=false;
        end
    end
end
end

function imRegion=getRegion(im,pt,maxvelocity,figsize)
pt=ceil(pt);
minx=pt(1)-maxvelocity+length(im(:,1))-floor(figsize(1))+1;
maxx=pt(1)+maxvelocity+length(im(:,1))-floor(figsize(1))+1;
miny=pt(2)-maxvelocity+length(im(1,:))-floor(figsize(2));
maxy=pt(2)+maxvelocity+length(im(1,:))-floor(figsize(2));

if minx<1
    minx=1;
elseif minx>length(im(:,1))
    minx=length(im(:,1));
end
if miny<1
    miny=1;
elseif miny>length(im(:,1))
    miny=length(im(:,1));
end
end

imRegion=im(miny:maxy,minx:maxx);

% --- Executes on button press in globalthresh.
function globalthresh_Callback(hObject, eventdata, handles)
% hObject handle to globalthresh (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of globalthresh
if get(hObject,'Value')==1
    frameno=str2double(get(handles.txtframeno,'String'));
    data=evalin('base','data');
    set(handles.minthresh,'Value',graythresh(data(:,1,frameno)));
    set(handles.manualthresh,'Enable','on');
else
    set(handles.manualthresh,'Enable','off');
    set(handles.manualthresh,'Value',0);
    set(handles.minthresh,'Enable','off');
end

% --- Executes during object creation, after setting all properties.
function slider9_CreateFcn(hObject, eventdata, handles)
% hObject handle to slider9 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: slider controls usually have a light gray background, change
% 'usewhitebg' to 0 to use default. See ISPC and COMPUTER.
usewhitebg = 1;
if usewhitebg
    set(hObject,'BackgroundColor',[.9 .9 .9]);
else
    set(hObject,'BackgroundColor',get(0,'defaultUicontrolBackgroundColor'));
end

% --- Executes on button press in localmanual.
function localmanual_Callback(hObject, eventdata, handles)
% hObject handle to localmanual (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of localmanual
if get(hObject,'Value')==1
    set(handles.localthreshslider,'Enable','on');
else
    set(handles.localthreshslider,'Enable','off');
end

```

```

end

% --- Executes on button press in localthresh.
function localthresh_Callback(hObject, eventdata, handles)
% hObject handle to localthresh (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hint: get(hObject,'Value') returns toggle state of localthresh
if get(hObject,'Value')==1
    frameno=str2double(get(handles.txtframeno,'String'));
    data=evalin('base','data');
    set(handles.localthreshslider,'Value',graythresh(data(:,:,1,frameno)));
    set(handles.localmanual,'Enable','on');
else
    set(handles.localmanual,'Enable','off');
    set(handles.localmanual,'Value',0);
    set(handles.localthreshslider,'Enable','off');
end

% --- Executes on button press in testglobal.
function testglobal_Callback(hObject, eventdata, handles)
% hObject handle to testglobal (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
data=evalin('base','data');
frameno=str2double(get(handles.txtframeno,'String'));
if get(handles.manualthresh,'Value')==1
    thresh=get(handles.mintthresh,'Value');
elseif get(handles.manualthresh,'Value')==0
    thresh=graythresh(data(:,:,1,frameno));
else
    mask=ones(length(data(:,1,1,1)),length(data(1,:,1,1)));
end
mask=data(:,:,1,frameno)>(thresh*max(max(data(:,:,1,frameno)))));
im=uint8(mask.*double(data(:,:,1,frameno)));

pos=[0.1200 0.09000 0.60 0.7450];
%pos=[29.8000 4.0331 108.0000 33.5458];

%check if prev fig drawn
fig1 = findobj('Tag','Fig1');
if ~isempty(fig1)
    delete(fig1)
end
axes('Position',pos);
h=subimage(m);
a1 = geth(Parent);
plotpoints(handles,frameno,eventdata);
%turn xandy value display off
set(a1,'Visible','off');
%save image tag
set(a1,'Tag','Fig1');
%set button down event for point selection
set(h,'ButtonDownFcn','warxutility(''Fig1_ButtonDownFcn'',gcbo,[],guidata(gcbo)))

% --- Executes on button press in loadbtn.
function loadbtn_Callback(hObject, eventdata, handles)
% hObject handle to loadbtn (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
filename=char(get(handles.savedataastextbox,'String'));
load(filename);
setappdata(handles.noPointsSelected,'pointSelect',noPointsSelected);

maxPsinFrame=max(noPointsSelected);
for i=1:maxPsinFrame
    str1=strcat(handles.point,int2str(i));
    str2=strcat('point',int2str(i));
    setappdata(eval(str1),str2,eval(str2));
end

% --- Executes on key press over txtframeno with no controls selected.
function txtframeno_KeyPressFcn(hObject, eventdata, handles)
% hObject handle to txtframeno (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% --- Executes on button press in CalcNewPts.
function CalcNewPts_Callback(hObject, eventdata, handles)
% hObject handle to CalcNewPts (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
frameno = str2double(get(handles.txtframeno,'String'))+1;
data=evalin('base','data');
set(handles.errormsg,'String','');
numPointsSelected = getappdata(handles.noPointsSelected,'pointSelect');
while (frameno <= length(data(1,1,1,:)))
    set(handles.txtframeno,'String',int2str(frameno));
    if strcmp(get(handles.errormsg,'String'),'')
        %If not manualsearch
        if get(handles.manualsearch,'Value')==0
            numfoundpt=0;
            foundpt=[0 0];
            for i = 1:numPointsSelected(frameno-1)
                str1=strcat(handles.point,int2str(i));
                str2=strcat('point',int2str(i));
                allpoints=getappdata(eval(str1),str2);
                if length(allpoints(:,1))<frameno
                    allpoints(frameno,1:2)=[0 0];
                end
                if (allpoints(frameno,1)==0)
                    [pt,found]=getNearestPt(handles,double(data(:,:,1,frameno)),i);
                    if found
                        numfoundpt=numfoundpt+1;
                        foundpt(numfoundpt,1:2)=pt;
                    else
                        break;
                    end
                end
            end
            %check all points found
            if (numfoundpt == numPointsSelected(frameno-1))&(checkLocality(foundpt,handles)==1)
                for i=1:numfoundpt
                    str1=strcat(handles.point,int2str(i));
                    str2=strcat('point',int2str(i));
                    allpoints=getappdata(eval(str1),str2);

```

```

        allpoints(frameo,1)=foundpt(i,1);
        allpoints(frameo,2)=foundpt(i,2);
        setappdata(eval(str1),str2,allpoints);
        numPointsSelected(frameo)=numPointsSelected(frameo)+1;
        setappdata(handles.noPointsSelected,'pointSelect',numPointsSelected);
    end
elseif numfoundpt ~= numPointsSelected(frameo-1)
    set(handles.manualsearch,'Value',1);
    set(handles.centssearch,'Value',0);
    set(handles.peaksearch,'Value',0);
    str='Not all points could be found';
    disp(str);
    set(handles.errormsg,'String',str);
    set(handles.errormsg,'Visible','on');
    beep;
    set(handles.txtframeo,'String',int2str(frameo-1));
    forwardbutton_Callback(eval(handles.forwardbutton), eventdata, handles);
    break;
end
end
frameo=frameo+1
end
end

```

Appendix 2.2 Algorithm for three dimensional reconstructions of marker locations from image based coordinates.

```
function dynamicDLT
% This Algorithm applies previously defined DLT constants to marker coordinates from each of 6 cameras
% and generates a three dimensional reconstruction of that point using the
% "RECONFU.m" algorithm of Reinschmidt, 1994
% Author: Warrick Mckinon
% Date: January 2006

load mdlinfo;
Ndynamicframes=input('how many real dynamic frames are there?: ');
save Ndynamicframes Ndynamicframes

copyfile('RECONFU.m','RFHD');
copyfile('RECONFU.m','LFHD');
copyfile('RECONFU.m','RBHD');
copyfile('RECONFU.m','LBHD');
copyfile('RECONFU.m','CLAV');
copyfile('RECONFU.m','STRN');
copyfile('RECONFU.m','C7');
copyfile('RECONFU.m','T10');
copyfile('RECONFU.m','RSHO');
copyfile('RECONFU.m','LSHO');
copyfile('RECONFU.m','RELB');
copyfile('RECONFU.m','LELB');
copyfile('RECONFU.m','RWRA');
copyfile('RECONFU.m','RWRB');
copyfile('RECONFU.m','LWRA');
copyfile('RECONFU.m','LWRB');
copyfile('RECONFU.m','RFIN');
copyfile('RECONFU.m','LFIN');
copyfile('RECONFU.m','RASI');
copyfile('RECONFU.m','LASI');
copyfile('RECONFU.m','SACR');
copyfile('RECONFU.m','RTHI');
copyfile('RECONFU.m','LTHI');
copyfile('RECONFU.m','RKNE');
copyfile('RECONFU.m','LKNE');
copyfile('RECONFU.m','RTIB');
copyfile('RECONFU.m','LTIB');
copyfile('RECONFU.m','RANK');
copyfile('RECONFU.m','LANK');
copyfile('RECONFU.m','RTOE');
copyfile('RECONFU.m','LTOE');
copyfile('RECONFU.m','TOP');
copyfile('RECONFU.m','BOTTOM');

cd('RFHD');save mdlinfo mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
disp 'RFHD'
load cam1xymarkercoords;
load cam2xymarkercoords;
load cam3xymarkercoords;
load cam4xymarkercoords;
load cam5xymarkercoords;load cam6xymarkercoords;

CAM1POS(1:Ndynamicframes,:)=cam1xymarkercoords(1:Ndynamicframes,:);
CAM2POS(1:Ndynamicframes,:)=cam2xymarkercoords(1:Ndynamicframes,:);
CAM3POS(1:Ndynamicframes,:)=cam3xymarkercoords(1:Ndynamicframes,:);
CAM4POS(1:Ndynamicframes,:)=cam4xymarkercoords(1:Ndynamicframes,:);
CAM5POS(1:Ndynamicframes,:)=cam5xymarkercoords(1:Ndynamicframes,:);CAM6POS(1:Ndynamicframes,:)=cam6xymarkercoords(1:Ndynamicframes,:);

CAMcoords(:,1:2) = CAM1POS;
CAMcoords(:,3:4) = CAM2POS;
CAMcoords(:,5:6) = CAM3POS;
CAMcoords(:,7:8) = CAM4POS;
CAMcoords(:,9:10) = CAM5POS; CAMcoords(:,11:12) = CAM6POS;
L=CAMcoords;
load mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
A=mdlinfo;
[H] = RECONFU(A,L);
RFHD=H;
save RFHD RFHD;
cd('.')
save RFHD RFHD;

cd('LFHD');save mdlinfo mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
disp 'LFHD'
load cam1xymarkercoords;
load cam2xymarkercoords;
load cam3xymarkercoords;
load cam4xymarkercoords;
load cam5xymarkercoords;load cam6xymarkercoords;

CAM1POS(1:Ndynamicframes,:)=cam1xymarkercoords(1:Ndynamicframes,:);
CAM2POS(1:Ndynamicframes,:)=cam2xymarkercoords(1:Ndynamicframes,:);
CAM3POS(1:Ndynamicframes,:)=cam3xymarkercoords(1:Ndynamicframes,:);
CAM4POS(1:Ndynamicframes,:)=cam4xymarkercoords(1:Ndynamicframes,:);
CAM5POS(1:Ndynamicframes,:)=cam5xymarkercoords(1:Ndynamicframes,:);

CAMcoords(:,1:2) = CAM1POS;
CAMcoords(:,3:4) = CAM2POS;
CAMcoords(:,5:6) = CAM3POS;
CAMcoords(:,7:8) = CAM4POS;
CAMcoords(:,9:10) = CAM5POS; CAMcoords(:,11:12) = CAM6POS;
L=CAMcoords;
load mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
A=mdlinfo;
[H] = RECONFU(A,L);
LFHD=H;
save LFHD LFHD;
cd('.')
save LFHD LFHD;

cd('RBHD');save mdlinfo mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
disp 'RBHD'
load cam1xymarkercoords;
load cam2xymarkercoords;
```

175

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177

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179

```

CAMcoords(:,1:2) = CAM1POS;
CAMcoords(:,3:4) = CAM2POS;
CAMcoords(:,5:6) = CAM3POS;
CAMcoords(:,7:8) = CAM4POS;
CAMcoords(:,9:10) = CAM5POS; CAMcoords(:,11:12) = CAM6POS;
L=CAMcoords;
load mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
A=mdlinfo;
[H] = RECONFU(A,L);
LTHI=H;
save LTHI LTHI;
cd('.')
save LTHI LTHI;

```

```

CAM1POS(1:Ndynamicframes,:)=cam1markercoords(1:Ndynamicframes,:);
CAM2POS(1:Ndynamicframes,:)=cam2markercoords(1:Ndynamicframes,:);
CAM3POS(1:Ndynamicframes,:)=cam3markercoords(1:Ndynamicframes,:);
CAM4POS(1:Ndynamicframes,:)=cam4markercoords(1:Ndynamicframes,:);
CAM5POS(1:Ndynamicframes,:)=cam5markercoords(1:Ndynamicframes,:);CAM6POS(1:Ndynamicframes,:)=cam6markercoords(1:Ndynamicframes,:);

```

```

CAM1POS(1:Ndynamicframes,:)=cam1xmarkercoords(1:Ndynamicframes,:);
CAM2POS(1:Ndynamicframes,:)=cam2xmarkercoords(1:Ndynamicframes,:);
CAM3POS(1:Ndynamicframes,:)=cam3xmarkercoords(1:Ndynamicframes,:);
CAM4POS(1:Ndynamicframes,:)=cam4xmarkercoords(1:Ndynamicframes,:);
CAM5POS(1:Ndynamicframes,:)=cam5xmarkercoords(1:Ndynamicframes,:);CAM6POS(1:Ndynamicframes,:)=cam6xmarkercoords(1:Ndynamicframes,:);

```

```
CAM1POS(1:Ndynamicframes,:)=cam1xmarkercoords(1:Ndynamicframes,:);
CAM2POS(1:Ndynamicframes,:)=cam2xmarkercoords(1:Ndynamicframes,:);
CAM3POS(1:Ndynamicframes,:)=cam3xmarkercoords(1:Ndynamicframes,:);
CAM4POS(1:Ndynamicframes,:)=cam4xmarkercoords(1:Ndynamicframes,:);
CAM5POS(1:Ndynamicframes,:)=cam5xmarkercoords(1:Ndynamicframes,:);CAM6POS(1:Ndynamicframes,:)=cam6xmarkercoords(1:Ndynamicframes,:);
```

```
cd(LTIB);save mdlinfo mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
disp 'LTIB'
load cam1xymarkercoords;
load cam2xymarkercoords;
load cam3xymarkercoords;
load cam4xymarkercoords;
load cam5xymarkercoords;load cam6xymarkercoords;
```

```
CAM1POS(1:Ndynamicframes,:)=cam1xymarkercoords(1:Ndynamicframes,:);
```

```

CAM2POS(1:Ndynamicframes,:)=cam2xymarkercoords(1:Ndynamicframes,:);
CAM3POS(1:Ndynamicframes,:)=cam3xymarkercoords(1:Ndynamicframes,:);
CAM4POS(1:Ndynamicframes,:)=cam4xymarkercoords(1:Ndynamicframes,:);
CAM5POS(1:Ndynamicframes,:)=cam5xymarkercoords(1:Ndynamicframes,:);CAM6POS(1:Ndynamicframes,:)=cam6xymarkercoords(1:Ndynamicframes,:);

CAMcoords(:,1:2) = CAM1POS;
CAMcoords(:,3:4) = CAM2POS;
CAMcoords(:,5:6) = CAM3POS;
CAMcoords(:,7:8) = CAM4POS;
CAMcoords(:,9:10) = CAM5POS; CAMcoords(:,11:12) = CAM6POS;
L=CAMcoords;
load mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
A=mdlinfo;
[H] = RECONFU(A,L);
LTOE=H;
save LTOE LTOE;
cd('.')
save LTOE LTOE;

cd('TOP');save mdlinfo mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
disp 'TOP'
load cam1xymarkercoords;
load cam2xymarkercoords;
load cam3xymarkercoords;
load cam4xymarkercoords;
load cam5xymarkercoords;load cam6xymarkercoords;

CAM1POS(1:Ndynamicframes,:)=cam1xymarkercoords(1:Ndynamicframes,:);
CAM2POS(1:Ndynamicframes,:)=cam2xymarkercoords(1:Ndynamicframes,:);
CAM3POS(1:Ndynamicframes,:)=cam3xymarkercoords(1:Ndynamicframes,:);
CAM4POS(1:Ndynamicframes,:)=cam4xymarkercoords(1:Ndynamicframes,:);
CAM5POS(1:Ndynamicframes,:)=cam5xymarkercoords(1:Ndynamicframes,:);CAM6POS(1:Ndynamicframes,:)=cam6xymarkercoords(1:Ndynamicframes,:);

CAMcoords(:,1:2) = CAM1POS;
CAMcoords(:,3:4) = CAM2POS;
CAMcoords(:,5:6) = CAM3POS;
CAMcoords(:,7:8) = CAM4POS;
CAMcoords(:,9:10) = CAM5POS; CAMcoords(:,11:12) = CAM6POS;
L=CAMcoords;
load mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
A=mdlinfo;
[H] = RECONFU(A,L);
TOP=H;
save TOP TOP;
cd('.')
save TOP TOP;

cd('BOTTOM');save mdlinfo mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
disp 'BOTTOM'
load cam1xymarkercoords;
load cam2xymarkercoords;
load cam3xymarkercoords;
load cam4xymarkercoords;
load cam5xymarkercoords;load cam6xymarkercoords;

CAM1POS(1:Ndynamicframes,:)=cam1xymarkercoords(1:Ndynamicframes,:);
CAM2POS(1:Ndynamicframes,:)=cam2xymarkercoords(1:Ndynamicframes,:);
CAM3POS(1:Ndynamicframes,:)=cam3xymarkercoords(1:Ndynamicframes,:);
CAM4POS(1:Ndynamicframes,:)=cam4xymarkercoords(1:Ndynamicframes,:);
CAM5POS(1:Ndynamicframes,:)=cam5xymarkercoords(1:Ndynamicframes,:);CAM6POS(1:Ndynamicframes,:)=cam6xymarkercoords(1:Ndynamicframes,:);

CAMcoords(:,1:2) = CAM1POS;
CAMcoords(:,3:4) = CAM2POS;
CAMcoords(:,5:6) = CAM3POS;
CAMcoords(:,7:8) = CAM4POS;
CAMcoords(:,9:10) = CAM5POS; CAMcoords(:,11:12) = CAM6POS;
L=CAMcoords;
load mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
A=mdlinfo;
[H] = RECONFU(A,L);
BOTTOM=H;
save BOTTOM BOTTOM;
cd('.')
save BOTTOM BOTTOM;
oldmdlinfo = mdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;
save oldmdlinfo oldmdlinfo; save Ndynamicframes;clear all; load Ndynamicframes ; load mdlinfo;

clear all
% need to delete mdlinfo or else the next trial that is performs will use old camera info
delete mdlinfo.mat

```

function GETDLTCONSTANTS

% This Algorithm generates DLT constants from calibration frame marker coordinates from each of 6 cameras
% and generates a file containing 6 sets of DLT calibration constants using the "mdlT.m" algorithm of
% Pribanic (1999)

% Author: Warrick Mckinon
% Date: January 2006

twelveactualcoords=[3.62 129.44 0; 183.37 124.99 0; 187.89 305.08 0; 7.68 309.45 0; 3.62 129.44 85.5; 183.37 124.99 85.6; 187.89 305.08 85.4; 7.68 309.45 85.35; 3.62 129.44 175.5; 183.37 124.99 175.6;
187.89 305.08 175.3; 7.68 309.45 175.4];

load marker_positions
pk=twelveactualcoords;
save('marker_positions','marker_positions');

%Cam1
sk=marker_positions(:,1);
sk=sk';
mdlT CAM1=mdlT1(pk,sk);
clear sk

%Cam2
sk=marker_positions(:,2);
sk=sk';
mdlT CAM2=mdlT1(pk,sk);
clear sk

%Cam3
sk=marker_positions(:,3);
sk=sk';
mdlT CAM3=mdlT1(pk,sk);
clear sk

%Cam4
sk=marker_positions(:,4); % it seems that MDLT is only using one camera????
sk=sk';
mdlT CAM4=mdlT1(pk,sk);
clear sk

%Cam5
sk=marker_positions(:,5);
sk=sk';
mdlT CAM5=mdlT1(pk,sk);
clear sk

%Cam6
sk=marker_positions(:,6); % it seems that MDLT is only using one camera????
sk=sk';
mdlT CAM6=mdlT1(pk,sk);
clear sk;

mdlTinfo=[mdlT CAM1,mdlT CAM2,mdlT CAM3,mdlT CAM4,mdlT CAM5,mdlT CAM6];
mdlTinfo=mdlTinfo(10:1:66);
mdlTinfo=[mdlTinfo(1:11);mdlTinfo(12:22);mdlTinfo(23:33);mdlTinfo(34:44);mdlTinfo(45:55);mdlTinfo(56:66)];
save('mdlTinfo','mdlTinfo');

clear all

Appendix 2.3 Algorithm for joint centre determination from marker locations

```

function gutsoFJCS
% This Algorithm applies marker set algorithm for the determination of joint centres
% details of each of the subroutines of this algorithm are specified in the
% appropriate places

%Authors: Warrick McKinon and Andrew Minett
%Date: January 2006

%*****
%* Lower Body Joint Centres Program *
%*****

%This program calculates the global coordinates of the HJC's - the minimum
%requirement for find the other joints in the lower body. The Program goes
%on to calculate the global coordinates for the joint centres in the rest
%of the lower body. Also calculates the coordinates of L5 based on the Plug
%in Gait Model presented by Vicon (based on Kadaba 1990 and
%Gutierrez 2003)

%The program uses Axis translation and rotation to switch between Global
%and local co-ordinate systems. Information about the origin of the local
%system of axes and the orientation of the local axes is contained in a
%matrix called the transition matrix.

%NOTE: It appears that the notation for defining matrices - A = (c;d) -
%denoting a matrix A is both incorrect and redundant. The definitions
%have, however, been left in the code. Taking the definitions out shouldnt
%change anything in the functioning of the program as matrices are defined
%by giving the variables real values as opposed to first defining the
%dimension of those variables. If anything, the "so-called" definition
%matrices should be removed so as to avoid redefining a variable that has
%already been calculated.

%*****
%* Sub-program HIP JOINT CENTRES *
%*****

%inputs: global coordinates of 3 surface markers - LASIS,
% RASIS, PelvisMarker
% Mean leglength & global variable MarkerRadius
%outputs: Left and right hip joint centres

lo=zeros(3,1); %position of local origin
Trans =zeros(4,4); %defines the transition matrix
PTrans = zeros(3,4); %defines the transition matrix before the placemark
%vector is included - the place marker vector occupies
%the first row of the transition matrix and serves to
%allow the transition matrix to be square and
%invertible

x = 1:4; %step value for initializing matrices
y = 1:4; %step value for initializing matrices
Trans(x,y) = 0; %initialize Trans matrix
Trans(1,:) = [1 0 0 0]; %initialises top row - place marker vector

currentRASIS = zeros(3,1); %defines vector for RASIS
currentLASIS = zeros(3,1); %defines vector for LASIS
SacrumMark = zeros(3,1); %defines vector for Sacrum Marker

currentRASIS = currentframe(1,1:3);
currentLASIS = currentframe(2,1:3);
SacrumMark = currentframe(3,1:3);%%I/C OUTPUT 33
% RASIS = [1 1 1];%%INPUT FROM RAW MARKER POSITION
% LASIS = [1 3 1];%%INPUT FROM RAW MARKER POSITION
% SacrumMark = [0 2 1];%%INPUT FROM RAW MARKER POSITION

%RASIS = input('Input the co-ordinates of RASIS in the form [x y z]:');
%LASIS = input('Input the co-ordinates of LASIS in the form [x y z]:');
%SacrumMark = input('Input the co-ordinates of Sacrum Marker:');

lo = (currentRASIS + currentLASIS)/2; %defines the local axis origin of the Pelvis
%Rigid SegmentA wrt global coords

Py = (currentLASIS - lo); %local unit vector y - orientation wrt global axes
UnitPy = Py/norm(Py);

RASIS2LASIS = currentLASIS - currentRASIS;
RASIS2SacrumMark = SacrumMark - currentRASIS;

Pz = cross(RASIS2LASIS,RASIS2SacrumMark); %cross means creat a new vector perpendicular to the plane they form, at vtheir origin%local unit vector z wrt global
UnitPz = Pz/norm(Pz);

Px = cross(UnitPy,UnitPz); %local unit vector x wrt global
UnitPx = Px/norm(Px);

x = 1:3;
PTrans(x,y) = 0; %initialize ptrans

PTrans(:,1) = lo; %input local origin to Ptransition matrix
PTrans(:,2) = UnitPx; %input x unit vector to Ptransition matrix
PTrans(:,3) = UnitPy; %input y unit vector to Ptransition matrix
PTrans(:,4) = UnitPz; %input z unit vector to Ptransition matrix
PTrans;

Trans(2,:) = PTrans(1,:); %input 1st row of PTrans into 2nd row of
Trans(3,:) = PTrans(2,:); %Trans etc...
Trans(4,:) = PTrans(3,:);
Trans; %Transition matrix of Rigid Segment PelvisA

% C = MeanLeg*0.115 - 15.3; but they use mm %calculates some value 'C' which is used
C = MeanLeg*0.115 - 1.53; %we use cm %in the calculation of the HJC - based on
%Plug-In-Gait by Vicon

cosT = cos(0.5); %These constants were calculated using
cosB = cos(0.314); %angles taken from Vicons Plug-In-Gait
sinT = sin(0.5); %paper. (Matlab takes angles in radians)
sinB = sin(0.314);

% AsisTrochDist = 0.1288*MeanLeg - 48.56; but they use mm %estimates the distance between

```

```

AsisTrochDist = 0.1288*MeanLeg - 4.856; %the trochlear and the asis
aa = norm(currentLASIS - lo); %half the length of the line
%joining the rasis and lasis

%LEFT HIP JOINT CENTRE - LOCAL

loLHJC4x1 = (4:1); %define vector for the local coords of the LHJC

loLHJCX = C*cosT*sinB - cosB*(AsisTrochDist + mm); %xcoord of LHJC wrt lo
loLHJCY = -(C*sinT) - aa; %ycoord of LHJC wrt lo
loLHJCZ = -C*cosT*cosB - sinB*(AsisTrochDist + mm); %zcoord of LHJC wrt lo
loLHJC4x1 = [1; loLHJCX; loLHJCY; loLHJCZ]; %enters the local co-ords
%into the loLHJC vector
loLHJC = [loLHJCX; loLHJCY; loLHJCZ];

%RIGHT HIP JOINT CENTRE - LOCAL

loRHJC4x1 = (4:1); %define vector for the local coords of the RHJC

loRHJCX = C*cosT*sinB - cosB*(AsisTrochDist + mm); %xcoord of RHJC wrt lo
loRHJCY = ((C*sinT) - aa); %ycoord of RHJC wrt lo
loRHJCZ = -C*cosT*cosB - sinB*(AsisTrochDist + mm); %zcoord of RHJC wrt lo
loRHJC4x1 = [1; loRHJCX; loRHJCY; loRHJCZ]; %enters the local co-ords
%into the loRHJC vector
loRHJC = [loRHJCX; loRHJCY; loRHJCZ];

%LEFT AND RIGHT GLOBAL HIP JOINT CENTRES

GL4x1 = Trans*loLHJC4x1; %Multiplication with the Transition Matrix to
GR4x1 = Trans*loRHJC4x1; %change to global co-ords

GLHJC = [GL4x1(2,1) GL4x1(3,1) GL4x1(4,1)];%%%JC OUTPUT
GRHJC = [GR4x1(2,1) GR4x1(3,1) GR4x1(4,1)];%%%JC OUTPUT

%*****
%* Sub Program CO-ORDINATES OF L5 *
%*****
%Find the coordinates of L5

loMidHJC = (loRHJC + loLHJC)/2; %The midpoint between the 2 HJC's in
%the local rigid system of axes PelvisA

loLumbar5 = loMidHJC + [0; 0; (0.828*(norm(GRHJC - GLHJC)))]
loLumbar54 = [1; loLumbar5];
GLumbar54 = Trans*loLumbar54; %Translating the Local co-ords of L5
%to Global
GLumbar5 = [GLumbar54(2,1) GLumbar54(3,1) GLumbar54(4,1)];%%%JC OUTPUT

%*****
%* Sub Program RIGHT KNEE JOINT CENTRE *
%*****
%inputs: global coordinates of 2 surface markers - Right Thigh Wand
% and Right Knee Marker - GRKneeMark, GRThighWand also takes the
% calculated hip joint centre - GRHJC
% Also takes the surface marker RKneeMarkInner to return the
% width of the knee
%outputs: Right knee joint centre - GRKJC

loOrigRKnee = (3:1);
RKneeTrans = (4:4);
RKneePTrans = (3:4);

x = 1:4; %step value for initializing matrices
y = 1:4; %step value for initializing matrices
RKneeTrans(x,y) = 0; %initializ Trans matrix

RKneeTrans(1,:) = [1 0 0 0]; %initialises top row - placemark vector

%Inputs:
GRKneeMark = (3:1);
GRThighWand = (3:1);
GRHJC;
% GRKneeMark = [1 3 1];%%%INPUT FROM RAW MARKER POSITION
% GRThighWand = [0 2 1];%%%INPUT FROM RAW MARKER POSITION
GRKneeMark = currentframe(4,1:3);
GRThighWand = currentframe(5,1:3);

%GRKneeMarkInner = [1 2 3]; %used for calculating the width of
%the knee

loOrigRKnee = (GRHJC + GRKneeMark)/2; %defines the local axis origin
%for the rigid segment right thigh
%wrt global coords

%Unit Vector generation - showing orientation wrt Global
RKnee2RHJC = GRHJC - GRKneeMark;
RKnee2RThighWand = GRThighWand - GRKneeMark;

UnitRLegX = RKnee2RHJC/norm(RKnee2RHJC);

RLegY = cross(RKnee2RHJC,RKnee2RThighWand);
UnitRLegY = RLegY/norm(RLegY);

RLegZ = cross(UnitRLegX,UnitRLegY);
UnitRLegZ = RLegZ/norm(RLegZ);

x = 1:3;
RKneePTrans(x,y) = 0; %initialize ptrans

RKneePTrans(:,1) = loOrigRKnee; %input loOrigRKnee to Pransition
RKneePTrans(:,2) = UnitRLegX; %input x unit vector to Pransition
RKneePTrans(:,3) = UnitRLegY; %input y unit vector to Pransition
RKneePTrans(:,4) = UnitRLegZ; %input z unit vector to Pransition

RKneeTrans(2,:) = RKneePTrans(1,:); %
RKneeTrans(3,:) = RKneePTrans(2,:); %
RKneeTrans(4,:) = RKneePTrans(3,:); %
RKneeTrans;

%Global to Local
InvRKneeTrans = inv(RKneeTrans);

GRHJC4 = [1 GRHJC];
GRKneeMark4 = [1 GRKneeMark];
GRThighWand4 = [1 GRThighWand];
%loOrigRKnee4 = [1 loOrigRKnee] %used in checking the conversion

loRHJC4 = InvRKneeTrans*transpose(GRHJC4);
loRKneeMark4 = InvRKneeTrans*transpose(GRKneeMark4);
loRThighWand4 = InvRKneeTrans*transpose(GRThighWand4);

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%check = InvRKneeTrans*transpose(loOrigRKnee4) %checks the conversion

%The three vectors below are the position vectors for RHJC, RKneeMark and
%RThighWand wrt the local axis for rigid segment right thigh
loRHJC = [loRHJC4(2,1) loRHJC4(3,1) loRHJC4(4,1)];
loRKneeMark = [loRKneeMark4(2,1) loRKneeMark4(3,1) loRKneeMark4(4,1)];
loRThighWand = [loRThighWand4(2,1) loRThighWand4(3,1) loRThighWand4(4,1)];

%the commented code below solves the circles simultaneously and becomes
%redundant once the solution is obtained - the solution being xA,xB,zA,zB
%syms x z a r1 r2;
%[x,z] = solve((x)^2 + (z)^2 - r1^2 , (x-a)^2 + (z)^2 - r2^2);

r1 = (norm(RKnee2RHJC))/2;
r2 = RKJCRadius/(norm(GRKneeMark - GRKneeMarkInner))/2;
a = -r1;

xA = 1/2*(a^2+r1^2-r2^2)/a;
xB = 1/2*(a^2+r1^2-r2^2)/a;

zA = 1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)^(1/2)/a;
zB = -1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)^(1/2)/a;

IntersectA = [xA 0 zA]; %may want to use the "crossfix" algorithm already in matlab later
IntersectB = [xB 0 zB];

chooseA = norm(IntersectA - loRThighWand);
chooseB = norm(IntersectB - loRThighWand);

if chooseA > chooseB;
    loRKJC = IntersectA;
else
    loRKJC = IntersectB;
end

loRKJC4 = [1 loRKJC];

GRKJC4 = RKneeTrans*transpose(loRKJC4);

GRKJC = [GRKJC4(2,1) GRKJC4(3,1) GRKJC4(4,1)];%%JC OUTPUT

%*****
%* Sub Program LEFT KNEE JOINT CENTRE *
%*****
%inputs: global coordinates of 2 surface markers - Left Thigh Wand
%         and Left Knee Marker - GLKneeMark, GLThighWand also takes the
%         calculated hip joint centre - GLHJC
%         Also takes the surface marker LKneeMarkInner to return the
%         width of the knee
%outputs: Left knee joint centre - GLKJC

loOrigLKnee = (3:1);
LKneeTrans = (4:4);
LKneePTrans = (3:4);

x = 1:4; %step value for initializing matrices
y = 1:4; %step value for initializing matrices
LKneeTrans(x,y) = 0; %initialize Trans matrix
LKneeTrans(1,:) = [1 0 0 0]; %fills top row - placemark vector

GLHJC;
GLKneeMark = (3:1);
GLThighWand = (3:1);
% GLKneeMark = [1 3 1];%%INPUT FROM RAW MARKER POSITION
% GLThighWand = [0 2 1];%%INPUT FROM RAW MARKER POSITION
GLKneeMark = currentframe(6,1:3);
GLThighWand = currentframe(7,1:3);

%GLKneeMarkInner = [1 2 3];

loOrigLKnee = (GLHJC + GLKneeMark)/2; %defines the local axis origin
%Rigid segment left thigh

LKnee2LHJC = GLHJC - GLKneeMark;
LKnee2LThighWand = GLThighWand - GLKneeMark;

UnitLLegX = LKnee2LHJC/norm(LKnee2LHJC);

LLegY = cross(LKnee2LThighWand,LKnee2LHJC);
UnitLLegY = LLegY/norm(LLegY);

LLegZ = cross(UnitLLegX,UnitLLegY);
UnitLLegZ = LLegZ/norm(LLegZ);

x = 1:3;
LKneePTrans(x,y) = 0; %initialize ptrans

LKneePTrans(:,1) = loOrigLKnee; %input loOrigLKnee origin to Ptrans
LKneePTrans(:,2) = UnitLLegX; %input x unit vector to Ptrans
LKneePTrans(:,3) = UnitLLegY; %input y unit vector to Ptrans
LKneePTrans(:,4) = UnitLLegZ; %input z unit vector to Ptrans

LKneeTrans(2,:) = LKneePTrans(1,:);
LKneeTrans(3,:) = LKneePTrans(2,:);
LKneeTrans(4,:) = LKneePTrans(3,:);
LKneeTrans;

%Global to Local

InvLKneeTrans = inv(LKneeTrans);

GLHJC4 = [1 GLHJC];
GLKneeMark4 = [1 GLKneeMark];
GLThighWand4 = [1 GLThighWand];
%loOrigLKnee4 = [1 loOrigLKnee];

loLHJC4 = InvLKneeTrans*transpose(GLHJC4);
loLKneeMark4 = InvLKneeTrans*transpose(GLKneeMark4);
loLThighWand4 = InvLKneeTrans*transpose(GLThighWand4);
%check = InvLKneeTrans*transpose(loOrigLKnee4)

loLHJC = [loLHJC4(2,1) loLHJC4(3,1) loLHJC4(4,1)];
loLKneeMark = [loLKneeMark4(2,1) loLKneeMark4(3,1) loLKneeMark4(4,1)];
loLThighWand = [loLThighWand4(2,1) loLThighWand4(3,1) loLThighWand4(4,1)];

%syms x z a r1 r2;

%[x,z] = solve((x)^2 + (z)^2 - r1^2 , (x-a)^2 + (z)^2 - r2^2);

r1 = (norm(LKnee2LHJC))/2;

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```

r2 = LKJCRadius;%(norm(GLKneeMark - GLKneeMarkInner))/2;
a = -r1;

xA = 1/2*(a^2+r1^2-r2^2)/a;
xB = 1/2*(a^2+r1^2-r2^2)/a;

zA = 1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)^(1/2)/a;
zB = -1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)^(1/2)/a;

IntersectA = [xA 0 zA];
IntersectB = [xB 0 zB];

chooseA = norm(IntersectA - loLThighWand);
chooseB = norm(IntersectB - loLThighWand);

if chooseA > chooseB;
    loL.KJC = IntersectA;
else
    loL.KJC = IntersectB;
end

loLKJC4 = [1 loL.KJC];

GLKJC4 = LKneeTrans*transpose(loLKJC4);

GLKJC = [GLKJC4(2,1) GLKJC4(3,1) GLKJC4(4,1)];%%%JC OUTPUT

%*****
%* Sub Program RIGHT ANKLE JOINT CENTRE *
%*****
%inputs:  global coordinates of 2 surface markers - Shank wand, lateral
%         malleolus - GRMalleolusMark, GRShankWand
%         Also takes the calculated Knee Joint centre - GRKJC
%         Also takes the surface marker GRMalleolusMarkInner to return
%         the width of the ankle
%outputs: Right Ankle joint centre - GRAJC

loOrigRcalf = (3:1);
RCalfTrans = (4:4);    %defines the transition matrix
RCalfPTrans = (3:4);    %defines the transition matrix before the
                        %placemaker vector is included

x = 1:4;                %step value for initializing matrices
y = 1:4;                %step value for initializing matrices
RCalfTrans(x,y) = 0;    %initialize Trans matrix

RCalfTrans(1,:) = [1 0 0 0];    %fills top row - placemaker vector

GRMalleolusMark = (3:1);
GRShankWand = (3:1);
GRKJC;
% GRMalleolusMark = [1 3 1];%%%INPUT FROM RAW MARKER POSITION
% GRShankWand = [0 2 1];%%%INPUT FROM RAW MARKER POSITION
GRMalleolusMark = currentframe(8,1:3);
GRShankWand = currentframe(9,1:3);

%GRMalleolusMarkInner = [1 2 3];

loOrigRcalf = (GRKJC + GRMalleolusMark)/2; %defines the local axes origin
                        %wrt global coords for the
                        %rigid segment Right Calf
RMalleolus2RKJC = GRKJC - GRMalleolusMark;
RMalleolus2RShankWand = GRShankWand - GRMalleolusMark;

%The three unit vectors below are used to indicate the orientation of the
%local axes for rigid segment right calf
UnitRShankX = RMalleolus2RKJC/norm(RMalleolus2RKJC);

RShankY = cross(RMalleolus2RKJC,RMalleolus2RShankWand);
UnitRShankY = RShankY/norm(RShankY);

RShankZ = cross(UnitRShankX,UnitRShankY);
UnitRShankZ = RShankZ/norm(RShankZ);

x = 1:3;
RCalfPTrans(x,y) = 0;    %initialize ptrans

RCalfPTrans(:,1) = loOrigRcalf;    %input loOrigRcalf origin to Ptrans
RCalfPTrans(:,2) = UnitRShankX;    %input x unit vector to Ptransition
RCalfPTrans(:,3) = UnitRShankY;    %input y unit vector to Ptransition
RCalfPTrans(:,4) = UnitRShankZ;    %input z unit vector to Ptransition

RCalfTrans(2,:) = RCalfPTrans(1,:);
RCalfTrans(3,:) = RCalfPTrans(2,:);
RCalfTrans(4,:) = RCalfPTrans(3,:);
RCalfTrans;

%Global to Local

InvRCalfTrans = inv(RCalfTrans);

GRKJC4 = [1 GRKJC];
GRMalleolusMark4 = [1 GRMalleolusMark];
GRShankWand4 = [1 GRShankWand];
%loOrigRcalf4 = [1 loOrigRcalf];

loRKJC4 = InvRCalfTrans*transpose(GRKJC4);
loRMalleolus4 = InvRCalfTrans*transpose(GRMalleolusMark4);
loRShankWand4 = InvRCalfTrans*transpose(GRShankWand4);
%check = InvRCalfTrans*transpose(loOrigRcalf4)

loRKJC = [loRKJC4(2,1) loRKJC4(3,1) loRKJC4(4,1)];
loRMalleolusMark = [loRMalleolus4(2,1) loRMalleolus4(3,1) loRMalleolus4(4,1)];
loRShankWand = [loRShankWand4(2,1) loRShankWand4(3,1) loRShankWand4(4,1)];

%syms x z a r1 r2;
%[x,z] = solve((x)^2 + (z)^2 - r1^2 , (x-a)^2 + (z)^2 - r2^2);

r1 = (norm(RMalleolus2RKJC))/2;
r2 = RAJCRadius;%(norm(GRMalleolusMark - GRMalleolusMarkInner))/2;
a = -r1;

xA = 1/2*(a^2+r1^2-r2^2)/a;
xB = 1/2*(a^2+r1^2-r2^2)/a;

zA = 1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)^(1/2)/a;
zB = -1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)^(1/2)/a;

IntersectA = [xA 0 zA];

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```

IntersectB = [xB 0 zB];

chooseA = norm(IntersectA - loRShankWand);
chooseB = norm(IntersectB - loRShankWand);

if chooseA > chooseB;
    loRAJC = IntersectA;
else
    loRAJC = IntersectB;
end

loRAJC4 = [1 loRAJC];

GRAJ/C4 = RCalfTrans*transpose(loRAJC4);

GRAJC = [GRAJ/C4(2,1) GRAJ/C4(3,1) GRAJ/C4(4,1)];%%%%JC OUTPUT

% *****
% * Sub Program LEFT ANKLE JOINT CENTRE *
% *****
%inputs:  global coordinates of 2 surface markers - Shank wand, lateral
%          malleolus - GLMalleolusMark, GLShankWand
%          Also takes the calculated Knee Joint centre - GLKJC
%          Also takes the surface marker GLMalleolusMarkInner to return
%          the width of the left ankle
%outputs: Left Ankle joint centre - GLAJC

loOrigLcalf = (3:1);
LCalfTrans = (4:4); %defines the transition matrix for the rigid
                %segment left calf
LCalfPTrans = (3:4); %defines the transition matrix before the
                %placemaker vector is included

x = 1:4; %step value for initializing matrices
y = 1:4; %step value for initializing matrices
LCalfTrans(x,y) = 0; %initialize Trans matrix

LCalfTrans(1,:) = [1 0 0 0]; %fills top row with placemaker vector

GLMalleolusMark = (3:1);
GLShankWand = (3:1);
GLKJC;
% GLMalleolusMark = [1 3 1];%%%%INPUT FROM RAW MARKER POSITION
% GLShankWand = [0 2 1];%%%%INPUT FROM RAW MARKER POSITION
GLMalleolusMark = currentframe(10,1:3);
GLShankWand = currentframe(11,1:3);

%GLMalleolusMarkInner = [1 2 3];

loOrigLcalf = (GLKJC + GLMalleolusMark)/2; %defines the origin of the
%local axis wrt global for the
%rigid segment left calf

LMalleolus2LKJC = GLKJC - GLMalleolusMark;
LMalleolus2LShankWand = GLShankWand - GLMalleolusMark;

%The three unit vectors below are used to indicate the orientation of the
%local axes for rigid segment right calf
UnitLShankX = LMalleolus2LKJC/norm(LMalleolus2LKJC);

LShankY = cross(LMalleolus2LShankWand,LMalleolus2LKJC);
UnitLShankY = LShankY/norm(LShankY);

LShankZ = cross(UnitLShankX,UnitLShankY);
UnitLShankZ = LShankZ/norm(LShankZ);

x = 1:3;
LCalfPTrans(x,y) = 0; %initialize ptrans

LCalfPTrans(:,1) = loOrigLcalf; %input loOrigLcalf origin to Ptrans
LCalfPTrans(:,2) = UnitLShankX; %input x unit vector to Ptransition
LCalfPTrans(:,3) = UnitLShankY; %input y unit vector to Ptransition
LCalfPTrans(:,4) = UnitLShankZ; %input z unit vector to Ptransition

LCalfTrans(2,:) = LCalfPTrans(1,:);
LCalfTrans(3,:) = LCalfPTrans(2,:);
LCalfTrans(4,:) = LCalfPTrans(3,:);
LCalfTrans;

%Global to Local

InvLCalfTrans = inv(LCalfTrans);

GLKJC4 = [1 GLKJC];
GLMalleolusMark4 = [1 GLMalleolusMark];
GLShankWand4 = [1 GLShankWand];
%loOrigLcalf4 = [1 loOrigLcalf];

loLKJC4 = InvLCalfTrans*transpose(GLKJC4);
loLMalleolus4 = InvLCalfTrans*transpose(GLMalleolusMark4);
loLShankWand4 = InvLCalfTrans*transpose(GLShankWand4);
%check = InvLCalfTrans*transpose(loOrigLcalf4)

loLKJC = [loLKJC4(2,1) loLKJC4(3,1) loLKJC4(4,1)];
loLMalleolusMark = [loLMalleolus4(2,1) loLMalleolus4(3,1) loLMalleolus4(4,1)];
loLShankWand = [loLShankWand4(2,1) loLShankWand4(3,1) loLShankWand4(4,1)];

%syms x z a r1 r2;
%[x,z] = solve((x)^2 + (z)^2 - r1^2 , (x-a)^2 + (z)^2 - r2^2);

r1 = (norm(LMalleolus2LKJC))/2;
r2 = LAJCRADIUS;%(norm(GLMalleolusMark - GLMalleolusMarkInner))/2;
a = -r1;

xA = 1/2*(a^2+r1^2-r2^2)/a;
xB = 1/2*(a^2+r1^2-r2^2)/a;

zA = 1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)^(1/2)/a;
zB = -1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)^(1/2)/a;

IntersectA = [xA 0 zA];
IntersectB = [xB 0 zB];

chooseA = norm(IntersectA - loLShankWand);
chooseB = norm(IntersectB - loLShankWand);

if chooseA > chooseB;
    loLAJC = IntersectA;
else
    loLAJC = IntersectB;
end

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loLAJC4 = [1 loLAJC];

GLAJC4 = LCalfTrans*transpose(loLAJC4);

GLAJC = [GLAJC4(2,1) GLAJC4(3,1) GLAJC4(4,1)];%%%JC OUTPUT

%*****
%* Sub Program RIGHT FOOT *
%*****
%inputs:  global coordinates of 1 surface marker - toe marker, RToeMarker
%         Also takes the calculated Knee Joint centre and Ankle joint
%         centre - GRKJC, GRAJC
%         Takes static measurement Ankle to toe tip - RAnkle2ToeTip
%outputs:  Right foot position - GRFoot

GRKJC;
GRAJC;
% RToeMarker = [0 2 1];%%%INPUT FROM RAW MARKER POSITION
RToeMarker = currentframe(13,1:3);

%RAnkle2ToeTip = 3;

loOrigRFoot = GRAJC;

GRAJC2RToe = RToeMarker - GRAJC;
GRAJC2RKJC = GRKJC - GRAJC;

%The three unit vectors below are used to indicate the orientation of the
%local axes for rigid segment Right Foot
UnitRFootX = GRAJC2RToe/norm(GRAJC2RToe);

RFootY = cross(GRAJC2RKJC,GRAJC2RToe);
UnitRFootY = RFootY/norm(RFootY);

RFootZ = cross(UnitRFootX,UnitRFootY);
UnitRFootZ = RFootZ/norm(RFootZ);

RFootTrans = (4:4);

x=1:4;
RFootTrans(x,x) = 0;

RFootTrans(1,:) = [1 0 0 0];

RFootPTrans = (3:4);
x = 1:3;
y = 1:4;
RFootPTrans(x,y) = 0;

RFootPTrans(:,1) = loOrigRFoot;
RFootPTrans(:,2) = UnitRFootX;
RFootPTrans(:,3) = UnitRFootY;
RFootPTrans(:,4) = UnitRFootZ;
RFootPTrans;

RFootTrans(2,:) = RFootPTrans(1,:);
RFootTrans(3,:) = RFootPTrans(2,:);
RFootTrans(4,:) = RFootPTrans(3,:);
% RFootTrans(3,2) = RFootPTrans(1,3);
% RFootTrans(4,2) = RFootPTrans(1,4);

RFootTrans;

loRFoot4 = [1; RAnkle2ToeTip ; 0 ; 0 ];

GRFoot4 = RFootTrans*loRFoot4;
GRFoot = [GRFoot4(2,1) GRFoot4(3,1) GRFoot4(4,1)];%%%JC OUTPUT

%*****
%* Sub Program LEFT FOOT *
%*****
%inputs:  global coordinates of 1 surface marker - toe marker, LToeMarker
%         Also takes the calculated Knee Joint centre and Ankle joint
%         centre - GLKJC, GLAJC
%         Takes static measurement Ankle to toe tip - LAnkle2ToeTip
%outputs:  Left foot position - GLFoot

GLKJC;
GLAJC;
% LToeMarker = [0 2 1];%%%INPUT FROM RAW MARKER POSITION
LToeMarker = currentframe(12,1:3);

%LAnkle2ToeTip = 3;

loOrigLFoot = GLAJC;

GLAJC2LToe = LToeMarker - GLAJC;
GLAJC2LKJC = GLKJC - GLAJC;

%The three unit vectors below are used to indicate the orientation of the
%local axes for rigid segment Right Foot
UnitLFootX = GLAJC2LToe/norm(GLAJC2LToe);

LFootY = cross(GLAJC2LKJC,GLAJC2LToe);
UnitLFootY = LFootY/norm(LFootY);

LFootZ = cross(UnitLFootX,UnitLFootY);
UnitLFootZ = LFootZ/norm(LFootZ);

LFootTrans = (4:4);

x=1:4;
LFootTrans(x,x) = 0;

LFootTrans(1,:) = [1 0 0 0];

LFootPTrans = (3:4);
x = 1:3;
y = 1:4;
LFootPTrans(x,y) = 0;

LFootPTrans(:,1) = loOrigLFoot;
LFootPTrans(:,2) = UnitLFootX;
LFootPTrans(:,3) = UnitLFootY;
LFootPTrans(:,4) = UnitLFootZ;
LFootPTrans;

LFootTrans(2,:) = LFootPTrans(1,:);
LFootTrans(3,:) = LFootPTrans(2,:);
LFootTrans(4,:) = LFootPTrans(3,:);

```

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LFootTrans;

loLFoot4 = [1 ; LAnkle2ToeTip ; 0 ; 0];

GLFoot4 = LFootTrans*loLFoot4;
GLFoot = [GLFoot4(2,1) GLFoot4(3,1) GLFoot4(4,1)];%%JC OUTPUT

%*****
%*****END*****
%*****

%*****
%* Upper Body Joint Centres Program *
%*****

%This program calculates the global coordinates of the SIC's - the minimum
%requirement for find the other joints in the Upper body. The Program goes
%on to calculate the global coordinates for the joint centres in the rest
%of the upper body.

%The program uses Axis translation and rotation to switch between Global
%and local co-ordinate systems. Information about the origin of the local
%system of axes and the orientation of the local axes is contained in a
%matrix called the transition matrix.

%*****
%* Sub Program THORAX TRANSITION *
%*****
%Thorax transision matrix

%inputs:  this program takes the coordinates of 4 chest markers:
%         MidClav, Sternum, CURRENTC7, CURRENTT10
%         The global variable mm is used
%outputs: Generation of the appropriate transition matrices and important
%         points for the calculation of the shoulder joint centres

MidClav = (3:1);
Sternum = (3:1);
CURRENTC7 = (3:1);
CURRENTT10 =(3:1);

currentRSHO = (3:1);
currentLSHO = (3:1);

ThoraxTrans = (4:4);
ThoraxPTrans = (3:4);

x = 1:4;      %step value for initializing matrices
y = 1:4;      %step value for initializing matrices
ThoraxTrans(x,y) = 0; %initializ Trans matrix
ThoraxTrans(1,:) = [1 0 0 0]; %insert placemarker vector

x = 1:3;
ThoraxPTrans(x,y) = 0;

% MidClav = [1 3 3];%%INPUT FROM RAW MARKER POSITION
% Sternum = [1 3 2];%%INPUT FROM RAW MARKER POSITION
% CURRENTC7 = [0 3 3];%%INPUT FROM RAW MARKER POSITION
% CURRENTT10 = [0 3 2];%%INPUT FROM RAW MARKER POSITION

% currentRSHO = [1 2 3];%%INPUT FROM RAW MARKER POSITION
% currentLSHO = [3 2 3];%%INPUT FROM RAW MARKER POSITION
MidClav = currentframe(14,1:3);
Sternum = currentframe(15,1:3);
CURRENTC7 = currentframe(16,1:3);
CURRENTT10 = currentframe(17,1:3);
currentRSHO = currentframe(18,1:3);
currentLSHO = currentframe(19,1:3);

Sho2Sho = norm(currentRSHO - currentLSHO);

MidPMidClav2C7 = (MidClav + CURRENTC7)/2;

MidPSternum2T10 = (Sternum + CURRENTT10)/2;

ThoraxZ = MidPMidClav2C7 - MidPSternum2T10;
UnitThoraxZ = ThoraxZ/norm(ThoraxZ);

SagittalPlanePointA = ThoraxZ/2 + MidPSternum2T10;
SagittalPlanePointB = (MidClav + Sternum)/2;
SagittalPlanePointC = MidPMidClav2C7;

PointA2C = SagittalPlanePointC - SagittalPlanePointA;
PointA2B = SagittalPlanePointB - SagittalPlanePointA;

ThoraxY = cross(PointA2C,PointA2B);
UnitThoraxY = ThoraxY/norm(ThoraxY);

ThoraxX = cross(ThoraxY,ThoraxZ);
UnitThoraxX = ThoraxX/norm(ThoraxX);

ThoraxAttitude = (3:3);
ThoraxAttitude(x,x) = 0;
ThoraxAttitude(:,1) = UnitThoraxX;
ThoraxAttitude(:,2) = UnitThoraxY;
ThoraxAttitude(:,3) = UnitThoraxZ;
ThoraxAttitude;

loOrigThorax = MidClav + [-mm 0 0]*ThoraxAttitude;

ThoraxPTrans(:,1) = loOrigThorax; %input loOrigThorax to Ptrans
ThoraxPTrans(:,2) = UnitThoraxX; %input x unit vector to Ptrans
ThoraxPTrans(:,3) = UnitThoraxY; %input y unit vector to Ptrans
ThoraxPTrans(:,4) = UnitThoraxZ; %input z unit vector to Ptrans

ThoraxTrans(2,:) = ThoraxPTrans(1,:); %
ThoraxTrans(3,:) = ThoraxPTrans(2,:); %
ThoraxTrans(4,:) = ThoraxPTrans(3,:); %
ThoraxTrans;

InvThoraxTrans = inv(ThoraxTrans);
%transpose([1 MidClav]); %used to test the loOrig of Thorax
%loMidClav = InvThoraxTrans*transpose([1 MidClav]);
%*****
%*****
%*****

```

```

%* Sub Program RIGHT SHOULDER JOINT CENTRE *
%*****

%inputs:  this program uses the information claculated in the thorax
%         transition program to generate local coordinate axes for the
%         rigid segment Right Shoulder - loOrigRSHO
%         also takes coordinates for the two shoulder markers:
%         currentRSHO,currentLSHO
%         The global variable mm is used as well as the scalar distance
%         between the two shoulders - Sho2Sho
%outputs:  this program outputs the position of the right
%         shoulder joint centre - RSJC

loOrigThorax2RSHO = currentRSHO - loOrigThorax;

loOrigThorax2RFake = cross(loOrigThorax2RSHO,UnitThoraxX);
%the above cross product is opposite to the cross product done on the left
%due to the properties of the cross product - this is needed to maintain a
%fake shoulder wand that is the same in the left
UnitloOrigThorax2RFake = loOrigThorax2RFake/norm(loOrigThorax2RFake);
GRFakeWand=(UnitloOrigThorax2RFake*norm(loOrigThorax2RSHO)*0.5)+loOrigThorax;
%The Magnitude of GRFakeWand is half that of the vector loOrigThorax2Rfake

%The check below ensures that the maths works
%loOrigThorax2RFakeWand = (UnitloOrigThorax2RFake*norm(loOrigThorax2RSHO)*0.5)
%loOrigThorax2RFakeWandCheck = GRFakeWand - loOrigThorax

%this was the original method of finding the SJC
%LSJC = currentLSHO + (Sho2Sho*[0 0 -0.2])*ThoraxAttitude;
%RSJC = currentRSHO + (Sho2Sho*[0 0 -0.2])*ThoraxAttitude;

%new axes setup
loOrigRSHO = (loOrigThorax + currentRSHO)/2;

RSHO2loOrigThorax = loOrigThorax - currentRSHO;

%Three unit vectors below indication the orientation of the local axis for
%rigid segment Right Shoulder
RSHOY = RSHO2loOrigThorax; %unit vector y in the direction from the
UnitRSHOY = RSHOY/norm(RSHOY); %right shoulder Marker to the loOrigThorax

RSHO2RFakeWand = GRFakeWand - currentRSHO;

RSHOZ = cross(RSHO2loOrigThorax,RSHO2RFakeWand);
UnitRSHOZ = RSHOZ/norm(RSHOZ);

RSHOX = cross(UnitRSHOY,UnitRSHOZ);
UnitRSHOX = RSHOX/norm(RSHOX);

x = 1:3;
RSHOPTrans(x,y) = 0; %initialize ptrans

RSHOPTrans(:,1) = loOrigRSHO; %input loOrigLSHO origin to Ptrans
RSHOPTrans(:,2) = UnitRSHOX; %input x unit vector to Ptransion
RSHOPTrans(:,3) = UnitRSHOY; %input y unit vector to Ptransion
RSHOPTrans(:,4) = UnitRSHOZ; %input z unit vector to Ptransion

RSHOTrans(1,:) = [1 0 0 0];
RSHOTrans(2,:) = RSHOPTrans(1,:); %
RSHOTrans(3,:) = RSHOPTrans(2,:); %
RSHOTrans(4,:) = RSHOPTrans(3,:); %
RSHOTrans;

GRFakeWand4 = [1 GRFakeWand];
loRSHOFakeWand4 = inv(RSHOPTrans)*transpose(GRFakeWand4);
loRSHOFakeWand = [loRSHOFakeWand4(2,1) loRSHOFakeWand4(3,1) loRSHOFakeWand4(4,1)];

%syms x y a r1 r2;

%[x,y] = solve(x^2 + y^2 - r1^2, x^2 + (y-a)^2 - r2^2);

r1 = (norm(loOrigThorax2RSHO))/2;
a = -r1;
r2 = 0.2*Sho2Sho; %radius of r2 is 0.2*dist(shoulder 2 shoulder)

xA = 1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2/2-r1^4+2*r1^2*r2^2-r2^4)*(1/2)/a;
xB = -1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2/2-r1^4+2*r1^2*r2^2-r2^4)*(1/2)/a;

yA = 1/2*(a^2+r1^2-r2^2)/a;
yB = 1/2*(a^2+r1^2-r2^2)/a;

IntersectA = [xA yA 0];
IntersectB = [xB yB 0];

chooseA = norm(IntersectA - loRSHOFakeWand);
chooseB = norm(IntersectB - loRSHOFakeWand);

if chooseA > chooseB;
    loRSJC = IntersectA;
else
    loRSJC = IntersectB;
end

loRSJC4 = [1 loRSJC];

GRSJC4 = RSHOTrans*transpose(loRSJC4);

GRSJC = [GRSJC4(2,1) GRSJC4(3,1) GRSJC4(4,1)];%%%JC OUTPUT

%*****
%* Sub Program LEFT SHOULDER JOINT CENTRE *
%*****

%inputs:  this program uses the information claculated in the thorax
%         transition program to generate local coordinate axes for the
%         rigid segment Left Shoulder - loOrigLSHO
%         also takes coordinates for the two shoulder markers:
%         currentRSHO,currentLSHO
%         The global variable mm is used as well as the scalar distance
%         between the two shoulders - Sho2Sho
%outputs:  this program outputs the position of the left
%         shoulder joint centre - LSJC

loOrigThorax2LSHO = currentLSHO - loOrigThorax;

loOrigThorax2Fake = cross(UnitThoraxX,loOrigThorax2LSHO);
UnitloOrigThorax2Fake = loOrigThorax2Fake/norm(loOrigThorax2Fake);
GLFakeWand = (UnitloOrigThorax2Fake*norm(loOrigThorax2LSHO)*0.5) + loOrigThorax;

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loOrigThorax2FakeWand = (UnitloOrigThorax2Fake*norm(loOrigThorax2LSHO)*0.5);

%this is the original method of finding the SJC
%LSJC = currentLSHO + (Sho2Sho*[0 0 -0.2])*ThoraxAttitude;
%GRSJC = currentRSHO + (Sho2Sho*[0 0 -0.2])*ThoraxAttitude;

%new axes setup
loOrigLSHO = (loOrigThorax + currentLSHO)/2;

LSHOY = loOrigThorax2LSHO;
UnitLSHOY = LSHOY/norm(LSHOY);

LSHOZ = cross(loOrigThorax2LSHO,loOrigThorax2FakeWand);
UnitLSHOZ = LSHOZ/norm(LSHOZ);

LSHOX = cross(UnitLSHOY,UnitLSHOZ);
UnitLSHOX = LSHOX/norm(LSHOX);

x = 1:3;
LSHOPTrans(x,y) = 0; %initialize ptrans

LSHOPTrans(:,1) = loOrigLSHO; %input loOrigLSHO origin to Ptrans
LSHOPTrans(:,2) = UnitLSHOX; %input x unit vector to Ptransition
LSHOPTrans(:,3) = UnitLSHOY; %input y unit vector to Ptransition
LSHOPTrans(:,4) = UnitLSHOZ; %input z unit vector to Ptransition

LSHOTrans(1,:) = [1 0 0 0];
LSHOTrans(2,:) = LSHOPTrans(1,:); %
LSHOTrans(3,:) = LSHOPTrans(2,:); %
LSHOTrans(4,:) = LSHOPTrans(3,:); %
LSHOTrans;

GLFakeWand4 = [1 GLFakeWand];
loLSHOFakeWand4 = inv(LSHOTrans)*transpose(GLFakeWand4);
loLSHOFakeWand = [loLSHOFakeWand4(2,1) loLSHOFakeWand4(3,1) loLSHOFakeWand4(4,1)];

%syms x y a r1 r2;

%[x,y] = solve(x^2 + y^2 - r1^2, x^2 + (y-a)^2 - r2^2);

r1 = (norm(loOrigThorax2LSHO))/2;
a = r1;
r2 = 0.2*Sho2Sho;

xA = 1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)*(1/2)/a;
xB = -1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)*(1/2)/a;

yA = 1/2*(a^2+r1^2-r2^2)/a;
yB = 1/2*(a^2+r1^2-r2^2)/a;

IntersectA = [xA yA 0];
IntersectB = [xB yB 0];

chooseA = norm(IntersectA - loLSHOFakeWand);
chooseB = norm(IntersectB - loLSHOFakeWand);

if chooseA > chooseB;
    loLSJC = IntersectA;
else
    loLSJC = IntersectB;
end

loLSJC4 = [1 loLSJC];

GLSJC4 = LSHOTrans*transpose(loLSJC4);

GLSJC = [GLSJC4(2,1) GLSJC4(3,1) GLSJC4(4,1)];%%JC OUTPUT

%*****
%* Sub Program RIGHT ELBOW JOINT CENTRE *
%*****

%inputs: the calculated Shoulder Joint centre - GRSJC
% Right elbow marker - GRElbow
% Right Lateral and medial wrist markers -
% RLatWrist, RMedWrist
% Takes inner elbow marker for calculation of elbow thickness -
% GRElbowInner
%outputs: this program outputs the position of the right
% Elbow joint centre - REJC

GRElbow = (3:1);
GRLatWrist = (3:1);
GRMedWrist = (3:1);

GRSJC;
% GRElbow = [2 3 5];%%INPUT FROM RAW MARKER POSITION
% GRLatWrist = [5 3 1];%%INPUT FROM RAW MARKER POSITION
% GRMedWrist = [6 2 3];%%INPUT FROM RAW MARKER POSITION
GRElbow = currentframe(20,1:3);
GRLatWrist = currentframe(22,1:3);
GRMedWrist = currentframe(21,1:3);

%GRElbowInner = [1 2 3];

GRWristMidpoint = (GRLatWrist + GRMedWrist)/2;

RElbow2RSJC = GRSJC - GRElbow;
RElbow2RWristMidpoint = GRWristMidpoint - GRElbow;

%the cross product taken for the left side of the body is opposite to this
%one in order that the fictitious wand is mirrored
Rdummy = cross(RElbow2RWristMidpoint,RElbow2RSJC);

GRArmWand = Rdummy + GRElbow; %co-ordinates for the fictitious arm wand

loOrigRElbow = (GRSJC + GRElbow)/2;

UnitRArmX = RElbow2RSJC/norm(RElbow2RSJC);

%this cross product is opposite on the left to ensure the general direction
%of the Y-axis is preserved on both sides of the body.
RArmY = cross(RElbow2RSJC,Rdummy);
UnitRArmY = RArmY/norm(RArmY);

RArmZ = cross(UnitRArmX,UnitRArmY);

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UnitRArmZ = RArmZ/norm(RArmZ);

RArmTrans = (4:4);
x = 1:4;
y = 1:4;
RArmTrans(x,y) = 0;
RArmTrans(1,:) = [1 0 0 0];
RArmPTrans = (3:4);
x = 1:3;
RArmPTrans(x,y) = 0; %initialize ptrans

RArmPTrans(:,1) = loOrigRElbow; %input loOrigRElbow to Ptrans
RArmPTrans(:,2) = UnitRArmX; %input x unit vector to Ptrans
RArmPTrans(:,3) = UnitRArmY; %input y unit vector to Ptrans
RArmPTrans(:,4) = UnitRArmZ; %input z unit vector to Ptrans

RArmTrans(2,:) = RArmPTrans(1,:); %
RArmTrans(3,:) = RArmPTrans(2,:); %
RArmTrans(4,:) = RArmPTrans(3,:); %
RArmTrans;

%Global to Local

InvRArmTrans = inv(RArmTrans);

GRSJIC4 = [1 GRSJC];
GRElbow4 = [1 GRElbow];
GRAMWand4 = [1 GRArmWand];
%loOrigRElbow4 = [1 loOrigRElbow]; %check tests the transformation

loRSJIC4 = InvRArmTrans*transpose(GRSJC4);
loRElbow4 = InvRArmTrans*transpose(GRElbow4);
loRArmWand4 = InvRArmTrans*transpose(GRAMWand4);
%check = InvRArmTrans*transpose(loOrigRElbow4)

loRSJIC = [loRSJIC4(2,1) loRSJIC4(3,1) loRSJIC4(4,1)];
loRKElbow = [loRElbow4(2,1) loRElbow4(3,1) loRElbow4(4,1)];
loRArmWand = [loRArmWand4(2,1) loRArmWand4(3,1) loRArmWand4(4,1)];

%syms x z a r1 r2;
%[x,z] = solve((x)^2 + (z)^2 - r1^2 , (x-a)^2 + (z)^2 - r2^2);

r1 = (norm(RElbow2RSJIC))/2;
r2 = RElbowRadius/(norm(GRElbow - GRElbowInner))/2;
a = -r1;

xA = 1/2*(a^2+r1^2-r2^2)/a;
xB = 1/2*(a^2+r1^2-r2^2)/a;

zA = 1/2*(-a^4+2*a^2*r1^2+a^2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)/(1/2)/a;
zB = -1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)/(1/2)/a;

IntersectA = [xA 0 zA];
IntersectB = [xB 0 zB];

chooseA_relb = norm(IntersectA - Rdummy);
chooseB_relb = norm(IntersectB - Rdummy);

if chooseA_relb < chooseB_relb;%Warrick changed this to less than and it seems to work
loREJC = IntersectA;
else
loREJC = IntersectB;
end

loREJC4 = [1 loREJC];

GREJC4 = RArmTrans*transpose(loREJC4);

GREJC = [GREJC4(2,1) GREJC4(3,1) GREJC4(4,1)];%%%JC OUTPUT

%*****
%* Sub Program LEFT ELBOW JOINT CENTRE *
%*****

%inputs: the calculated Shoulder Joint centre - GLSJC
% Left elbow marker - GLElbow
% Left Lateral and medial wrist markers -
% LLatWrist, LMedWrist
% Takes inner elbow marker for calculation of elbow thickness -
% GLElbowInner
%outputs: this program outputs the position of the left
% Elbow joint centre - LEJC

GLElbow = (3:1);
GLLatWrist = (3:1);
GLMedWrist = (3:1);

GLSJC;
% GLElbow = [2 3 5];%%INPUT FROM RAW MARKER POSITION
% GLLatWrist = [5 3 1];%%INPUT FROM RAW MARKER POSITION
% GLMedWrist = [6 2 3];%%INPUT FROM RAW MARKER POSITION
GLElbow = currentframe(23,1:3);
GLLatWrist = currentframe(25,1:3);
GLMedWrist = currentframe(24,1:3);

%GLElbowInner = [1 2 3];

GLWristMidpoint = (GLLatWrist + GLMedWrist)/2;

LElbow2LSJC = GLSJC - GLElbow;
LElbow2LWristMidpoint = GLWristMidpoint - GLElbow;

%create a fictitious wand perpendicular to the plane formed by the 3 points
%midwrist, elbow marker and shoulder joint centre
Ldummy = cross(LElbow2LSJC,LElbow2LWristMidpoint);

GLArmWand = Ldummy + GLElbow;

loOrigLElbow = (GLSJC + GLElbow)/2;

UnitLArmX = LElbow2LSJC/norm(LElbow2LSJC);

LArmY = cross(Ldummy,LElbow2LSJC);
UnitLArmY = LArmY/norm(LArmY);

LArmZ = cross(UnitLArmX,UnitLArmY);
UnitLArmZ = LArmZ/norm(LArmZ);

RArmTrans = (4:4);
x = 1:4;

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y = 1:4;
LArmTrans(x,y) = 0;
LArmTrans(1,:) = [1 0 0 0];
LArmPTrans = (3:4);
x = 1:3;
LArmPTrans(x,y) = 0; %initialize ptrans

LArmPTrans(:,1) = loOrigLElbow; %input loOrigLElbow to Ptrans
LArmPTrans(:,2) = UnitLArmX; %input x unit vector to Ptrans
LArmPTrans(:,3) = UnitLArmY; %input y unit vector to Ptrans
LArmPTrans(:,4) = UnitLArmZ; %input z unit vector to Ptrans

LArmTrans(2,:) = LArmPTrans(1,:);
LArmTrans(3,:) = LArmPTrans(2,:);
LArmTrans(4,:) = LArmPTrans(3,:);
LArmTrans;

%Global to Local

InvLArmTrans = inv(LArmTrans);

GLSJC4 = [1 GLSJC];
GLElbow4 = [1 GLElbow];
GLArmWand4 = [1 GLArmWand];
%loOrigLElbow4 = [1 loOrigLElbow];

loLSJC4 = InvLArmTrans*transpose(GLSJC4);
loLElbow4 = InvLArmTrans*transpose(GLElbow4);
loLArmWand4 = InvLArmTrans*transpose(GLArmWand4);
%check = InvLArmTrans*transpose(loOrigLElbow4)

loLSJC = [loLSJC4(2,1) loLSJC4(3,1) loLSJC4(4,1)];
loKElbow = [loLElbow4(2,1) loLElbow4(3,1) loLElbow4(4,1)];
loLArmWand = [loLArmWand4(2,1) loLArmWand4(3,1) loLArmWand4(4,1)];

%syms x z a r1 r2;
%[x,z] = solve((x)^2 + (z)^2 - r1^2 , (x-a)^2 + (z)^2 - r2^2);

r1 = (norm(LElbow2LSJC))/2;
r2 = LElbowRadius/(norm(GLElbow - GLElbowInner))/2;
a = +1;

xA = 1/2*(a^2+r1^2-r2^2)/a;
xB = 1/2*(a^2+r1^2-r2^2)/a;

zA = 1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)*(1/2)/a;
zB = -1/2*(-a^4+2*r1^2*a^2+2*a^2*r2^2-r1^4+2*r1^2*r2^2-r2^4)*(1/2)/a;

IntersectA = [xA 0 zA];
IntersectB = [xB 0 zB];

chooseA_elb = norm(IntersectA - Ldummy);
chooseB_elb = norm(IntersectB - Ldummy);

if chooseA_elb > chooseB_elb;
    loEJC = IntersectA;
else
    loEJC = IntersectB;
end

loLEJC4 = [1 loLEJC];

GLEJC4 = LArmTrans*transpose(loLEJC4);

GLEJC = [GLEJC4(2,1) GLEJC4(3,1) GLEJC4(4,1)];%%%%JC OUTPUT

%*****
%* Sub Program RIGHT WRIST JOINT CENTRE *
%*****

%Inputs: Calculated elbow Joint centre - GREJC
% medial and lateral, right wrist markers - GRLatWrist,
% GRMedWrist
% Wrist thickness is also used
%Plane defined by the following 3 markers: GREJC,GRLatWrist,GRMedWrist
%Output: Position of the Right Wrist joint centre - GRWJC

loOrigRWrist = (3:1);

GREJC;
GRLatWrist;
GRMedWrist;
GRWristMidpoint;
loOrigRWrist = GRWristMidpoint;

%RWristThickness = 1;%static

RWristY = GRWristMidpoint - GRLatWrist;
UnitRWristY = RWristY/norm(RWristY);

GRLatWrist2GREJC = GREJC - GRLatWrist;
GRLatWrist2GRMedWrist = GRMedWrist - GRLatWrist;

%This cross product is opposite in left to maintain similar axis
%orientation for both sides
% RWristX = cross(GRLatWrist2GRMedWrist,GRLatWrist2GREJC);%warrick changed because seems to be the wrong direction
RWristX = cross(GRLatWrist2GREJC,GRLatWrist2GRMedWrist);

UnitRWristX = RWristX/norm(RWristX);

RWristZ = cross(UnitRWristX,UnitRWristY);
UnitRWristZ = RWristZ/norm(RWristZ);
RWristThicknessoffset=RWristThickness/2;%warrick made this change????????????
% loRWJC4 = [1 ; RWristThickness ; 0 ; 0];
loRWJC4 = [1 ; RWristThicknessoffset ; 0 ; 0];

RWristTrans = (4:4);
x = 1:4;
y = 1:4;
RWristTrans(x,y) = 0;
RWristTrans(1,:) = [1 0 0 0];
RWristPTrans = (3:4);
x = 1:3;
RWristPTrans(x,y) = 0; %initialize ptrans

RWristPTrans(:,1) = loOrigRWrist; %input Local origin to Ptrans
RWristPTrans(:,2) = UnitRWristX; %input x unit vector to Ptrans
RWristPTrans(:,3) = UnitRWristY; %input y unit vector to Ptrans

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RWristPTrans(:,4) = UnitRWristZ; %input z unit vector to Ptrans

RWristTrans(2,:) = RWristPTrans(1,:);
RWristTrans(3,:) = RWristPTrans(2,:);
RWristTrans(4,:) = RWristPTrans(3,:);
RWristTrans;

GRWJC4 = RWristTrans*loRWJC4;
GRWJC = [GRWJC4(2,1) GRWJC4(3,1) GRWJC4(4,1)];%%%JC OUTPUT

%*****
%* Sub Program LEFT WRIST JOINT CENTRE *
%*****

%Inputs: Calculated elbow Joint centre - GLEJC
% medial and lateral, left wrist markers - GLLatWrist,
% GLMedWrist
% Wrist thickness is also used
%Plane defined by the following 3 markers: GLEJC,GLLatWrist,GLMedWrist
%Output: Position of the Left Wrist joint centre - GLWJC

loOrigLWrist = (3:1);

GLEJC;
GLLatWrist;
GLMedWrist;
GLWristMidpoint = (GLLatWrist + GLMedWrist)/2;
loOrigLWrist = GLWristMidpoint;

%LWristThickness = 1;%static

LWristY = GLLatWrist - GLWristMidpoint;
UnitLWristY = LWristY/norm(LWristY);

GLLatWrist2GLEJC = GLEJC - GLLatWrist;
GLLatWrist2GLMedWrist = GLMedWrist - GLLatWrist;

% LWristX = cross(GLLatWrist2GLEJC,GLLatWrist2GLMedWrist);%warrick changed because seems to be the wrong direction
LWristX = cross(GLLatWrist2GLMedWrist,GLLatWrist2GLEJC);
UnitLWristX = LWristX/norm(LWristX);

LWristZ = cross(UnitLWristX,UnitLWristY);
UnitLWristZ = LWristZ/norm(LWristZ);
LWristThicknessoffset=LWristThickness/2;%warrick made this change????????????
% loLWJC4 = [1 ; LWristThickness ; 0 ; 0];
% loLWJC4 = [1 ; LWristThicknessoffset ; 0 ; 0];

LWristTrans = (4:4);
x = 1:4;
y = 1:4;
LWristTrans(x,y) = 0;
LWristTrans(1,:) = [1 0 0 0];
LWristPTrans = (3:4);
x = 1:3;
LWristPTrans(x,y) = 0; %initialize ptrans

LWristPTrans(:,1) = loOrigLWrist; %input loOrigLWrist to Ptrans
LWristPTrans(:,2) = UnitLWristX; %input x unit vector to Ptrans
LWristPTrans(:,3) = UnitLWristY; %input y unit vector to Ptrans
LWristPTrans(:,4) = UnitLWristZ; %input z unit vector to Ptrans

LWristTrans(2,:) = LWristPTrans(1,:);
LWristTrans(3,:) = LWristPTrans(2,:);
LWristTrans(4,:) = LWristPTrans(3,:);
LWristTrans;

GLWJC4 = LWristTrans*loLWJC4;
GLWJC = [GLWJC4(2,1) GLWJC4(3,1) GLWJC4(4,1)];%%%JC OUTPUT

%*****
%* Sub Program RIGHT HAND *
%*****

%Inputs: Calculated Wrist Joint centre - GRWJC
% right Mipoint of wrist marker - GRWristMidpoint
% Finger marker - GRFinger
% Static Measurement - RHandThickness
%Plane defined by the following 3 markers: GRWJC, GRWristMidpoint, GRFinger
%outputs: Global Co-ords for the right hand GRHC

GRHC = (3:1);
GRWJC;
GRFinger = (3:1);
GRLatWrist;
GRMedWrist;
loOrigRHand = (3:1);

GRWJC;
GRLatWrist;
GRMedWrist;
% GRFinger = [2 4 1];%%%INPUT FROM RAW MARKER POSITION
GRFinger = currentframe(26,1:3);

%RHandThickness = 1;%static

GRWristMidpoint;
loOrigRHand = (GRWJC + GRFinger)/2;

GRFinger2GRWJC = (GRWJC - GRFinger);
GRFinger2GRWristMidpoint = (GRWristMidpoint - GRFinger);

UnitRHandZ = GRFinger2GRWJC/norm(GRFinger2GRWJC);

RHandY = cross(GRFinger2GRWristMidpoint,GRFinger2GRWJC);
UnitRHandY = RHandY/norm(RHandY);

RHandX = cross(UnitRHandY,UnitRHandZ);
UnitRHandX = RHandX/norm(RHandX);

RHandTrans = (4:4);
x = 1:4;
y = 1:4;
RHandTrans(x,y) = 0;
RHandTrans(1,:) = [1 0 0 0];
RHandPTrans = (3:4);
x = 1:3;
RHandPTrans(x,y) = 0; %initialize ptrans

```

```

RHandPTrans(:,1) = loOrigRHand;    %input Local origin to Ptrans
RHandPTrans(:,2) = UnitRHandX;    %input x unit vector to Ptrans
RHandPTrans(:,3) = UnitRHandY;    %input y unit vector to Ptrans
RHandPTrans(:,4) = UnitRHandZ;    %input z unit vector to Ptrans

RHandTrans(2,:) = RHandPTrans(1,:);
RHandTrans(3,:) = RHandPTrans(2,:);
RHandTrans(4,:) = RHandPTrans(3,:);
RHandTrans;

InvRHandTrans = inv(RHandTrans);

GRFinger4 = [1 GRFinger];
loRFinger4 = InvRHandTrans*transpose(GRFinger4);

%syms x z a r1 r2;
%[x,z] = solve((x)^2 + (z)^2 - r1^2, (x)^2 + (z-a)^2 - r2^2);

r1 = norm(loOrigRHand - GRFinger);
r2 = RHandThickness/2;
a = -r1;

xA = 1/2*(-r1^4+2*r1^2*a^2+2*r1^2*r2^2/2-a^4+2*a^2*r2^2-r2^4)^(1/2)/a;
xB = -1/2*(-r1^4+2*r1^2*a^2+2*r1^2*r2^2/2-a^4+2*a^2*r2^2-r2^4)^(1/2)/a;

zA = 1/2*(r1^2+a^2-r2^2)/a;
zB = 1/2*(r1^2+a^2-r2^2)/a;

IntersectA = [xA 0 zA];
IntersectB = [xB 0 zB];

chooseA_RHand = norm(IntersectA - GRWristMidpoint);
chooseB_RHand = norm(IntersectB - GRWristMidpoint);

if chooseA_RHand < chooseB_RHand;%warrick changed this to "<"
    loRHC = IntersectA;
else
    loRHC = IntersectB;
end

loRHC4 = [1 loRHC];

GRHC4 = RHandTrans*transpose(loRHC4);

GRHC = [GRHC4(2,1) GRHC4(3,1) GRHC4(4,1)];%%%%C OUTPUT

%*****
%* Sub Program LEFT HAND *
%*****

%Inputs:  Calculated Wrist Joint centre - GLWJC
%         left Mipoint of wrist marker - GLWristMidpoint
%         Finger marker - GLFinger
%         Static Measurement - LHandThickness
%Plane defined by the following 3 markers: GLWJC, GLWristMidpoint, GLFinger
%outputs:  Global Co-ords for the right hand GRHC

GLHC = (3:1);
GLWJC;
GLFinger = (3:1);
GLLatWrist;
GLMedWrist;
loOrigLHand = (3:1);

GLWJC;
GLLatWrist;
GLMedWrist;
% GLFinger = [2 4 1];%%%%INPUT FROM RAW MARKER POSITION
GLFinger = currentframe(27,1:3);

%LHandThickness = 1;%static

GLWristMidpoint;
loOrigLHand = (GLWJC + GLFinger)/2;

GLFinger2GLWJC = (GLWJC - GLFinger);
GLFinger2GLWristMidpoint = (GLWristMidpoint - GLFinger);

UnitLHandZ = GLFinger2GLWJC/norm(GLFinger2GLWJC);

LHandY = cross(GLFinger2GLWristMidpoint, GLFinger2GLWJC);
UnitLHandY = LHandY/norm(LHandY);

LHandX = cross(UnitLHandY, UnitLHandZ);
UnitLHandX = LHandX/norm(LHandX);

LHandTrans = (4:4);
x = 1:4;
y = 1:4;
LHandTrans(x,y) = 0;
LHandTrans(1,:) = [1 0 0 0];
LHandPTrans = (3:4);
x = 1:3;
LHandPTrans(x,y) = 0; %initialize ptrans

LHandPTrans(:,1) = loOrigLHand;    %input Local origin to Ptrans
LHandPTrans(:,2) = UnitLHandX;    %input x unit vector to Ptrans
LHandPTrans(:,3) = UnitLHandY;    %input y unit vector to Ptrans
LHandPTrans(:,4) = UnitLHandZ;    %input z unit vector to Ptrans

LHandTrans(2,:) = LHandPTrans(1,:);
LHandTrans(3,:) = LHandPTrans(2,:);
LHandTrans(4,:) = LHandPTrans(3,:);
LHandTrans;

InvLHandTrans = inv(LHandTrans);

GLFinger4 = [1 GLFinger];
loLFinger4 = InvLHandTrans*transpose(GLFinger4);

%syms x z a r1 r2;
%[x,z] = solve((x)^2 + (z)^2 - r1^2, (x)^2 + (z-a)^2 - r2^2);

r1 = norm(loOrigLHand - GLFinger);
r2 = LHandThickness/2;
a = -r1;

```

```

xA = 1/2*(r1^4+2*r1^2*a^2+2*r1^2*r2^2-a^4+2*a^2*r2^2-r2^4)^(1/2)/a;
xB = -1/2*(r1^4+2*r1^2*a^2+2*r1^2*r2^2-a^4+2*a^2*r2^2-r2^4)^(1/2)/a;

zA = 1/2*(r1^2+a^2-r2^2)/a;
zB = 1/2*(r1^2-a^2-r2^2)/a;

IntersectA = [xA 0 zA];
IntersectB = [xB 0 zB];

chooseA_LHand = norm(IntersectA - GLWristMidpoint);
chooseB_LHand = norm(IntersectB - GLWristMidpoint);

if chooseA_LHand < chooseB_LHand;%warrick changed this to "<"
    loLHC = IntersectA;
else
    loLHC = IntersectB;
end

loLHC4 = [1 loLHC];

GLHC4 = LHandTrans*transpose(loLHC4);

GLHC = [GLHC4(2,1) GLHC4(3,1) GLHC4(4,1)];%%%JC OUTPUT

%*****
%*****END*****
%*****
%*****

%*****
%* Program for approximating the centre of mass of rigid segments *
%*****

%This program uses guidelines given by ..... to calculate the CoM of
%all the segments of the body and uses these CoM components to calculate
%the CoM of the entire body

%The program uses Axis translation and rotation to switch between Global
%and local co-ordinate systems. Information about the origin of the local
%system of axes and the orientation of the local axes is contained in a
%matrix called the transition matrix.

%*****
%* Sub Program PELVIS CENTRE *
%*****
%Inputs:  uses the calculated positions of left and right HJC and the 5th
%         lumbar vertebra - GLHJC, GRHJC, GLumbar5
%Outputs: the CoM of the pelvis - GPelCentre
%Pelvis, Head

GLHJC;
GRHJC;
GLumbar5;

GMidHJC = (GLHJC + GRHJC)/2;

loOrigPelvis = GMidHJC; %this defines the position wrt global co-ordinates
%of the local axis for rigid segment PELVIS B.
%NB: not the same as the local coords in the HJC's
%section of code

GRHJC2GLHJC = GLHJC - GRHJC;
GRHJC2GLumbar5 = GLumbar5 - GRHJC;

PelvisZ = GLumbar5 - GMidHJC;
UnitPelvisZ = PelvisZ/norm(PelvisZ);

PelvisX = cross(GRHJC2GLHJC, GRHJC2GLumbar5);
UnitPelvisX = PelvisX/norm(PelvisX);

PelvisY = cross(UnitPelvisZ, UnitPelvisX);
UnitPelvisY = PelvisY/norm(PelvisY);

PelvisTrans = (4:4);

x = 1:4;
y = 1:4;
PelvisTrans(x,y) = 0;

PelvisTrans(1,:) = [1 0 0 0];

PelvisPTrans = (3:4);
x = 1:3;
PelvisPTrans(x,y) = 0;

PelvisPTrans(:,1) = loOrigPelvis;
PelvisPTrans(:,2) = UnitPelvisX;
PelvisPTrans(:,3) = UnitPelvisY;
PelvisPTrans(:,4) = UnitPelvisZ;
PelvisPTrans;

PelvisTrans(2,:) = PelvisPTrans(1,:);
PelvisTrans(3,:) = PelvisPTrans(2,:);
PelvisTrans(4,:) = PelvisPTrans(3,:);
PelvisTrans;

loPelCentre = [0 0 (0.925*(norm(GLHJC - GRHJC)))]';
loPelCentre4 = [1 loPelCentre];
GPelCentre4 = PelvisTrans*transpose(loPelCentre4);

GPelCentre = [GPelCentre4(2,1) GPelCentre4(3,1) GPelCentre4(4,1)];%%%JC OUTPUT

%*****
%* Sub Program HEAD CENTRE *
%*****
%Inputs:  Takes the co-ords of 4 head surface markers - GLFHead, GRFHead,
%         GLBHead, GRBHead
%Outputs: the CoM of the Head - HeadCentre

% GLFHead = [2 3 4];%%INPUT FROM RAW MARKER POSITION
% GRFHead = [1 3 1];%%INPUT FROM RAW MARKER POSITION
% GLBHead = [7 3 1];%%INPUT FROM RAW MARKER POSITION
% GRBHead = [7 3 4];%%INPUT FROM RAW MARKER POSITION
GLFHead = currentframe(28,1:3);
GRFHead = currentframe(29,1:3);
GLBHead = currentframe(30,1:3);
GRBHead = currentframe(31,1:3);

```

```

%The local origin and unit vectors below can be used to from a head
%transition matrix, but for the calculation of the position of the head
%CoM for the rigid segment HEAD the transition matrix is not a requirement
loOrigHead = (GLFHead + GRFHead)/2;

HeadY = GLFHead - GRFHead;
UnitHeadY = HeadY/norm(HeadY);

loOrigHead2GLBHead = GLBHead - loOrigHead;
loOrigHead2GRBHead = GRBHead - loOrigHead;

HeadZ = cross(loOrigHead2GLBHead,loOrigHead2GRBHead);
UnitHeadZ = HeadZ/norm(HeadZ);

HeadX = cross(UnitHeadY,UnitHeadZ);
UnitHeadX = HeadX/norm(HeadX);

GMidBackHead = (GLBHead + GRBHead)/2;

loOrigHead2GMidBackHead = GMidBackHead - loOrigHead;

HeadCentre = 0.52*(loOrigHead2GMidBackHead) + loOrigHead;%%%JC OUTPUT


%Calculates the Right Arm CoM
%Inputs: GREJC, GRSJC
%*****

RArmCentre = (GREJC - GRSJC)*RArmFactor + GRSJC;%%%JC OUTPUT

%Calculates the Left Arm CoM
%Inputs: GLEJC, GLSJC
%*****

LArmCentre = (GLEJC - GLSJC)*LArmFactor + GLSJC;%%%JC OUTPUT

%Calculates the Right Forearm CoM
%Inputs: GREJC, GRWJC
%*****

RForearmCentre = (GRWJC - GREJC)*RForearmFactor + GREJC;%%%JC OUTPUT

%Calculates the Left Forearm CoM
%Inputs: GLEJC, GLWJC
%*****

LForearmCentre = (GLWJC - GLEJC)*LForearmFactor + GLEJC;%%%JC OUTPUT

%Calculates the Right Hand CoM
%Inputs: GRHC, GRWJC
%*****

RHandCentre = (GRHC - GRWJC)*RHandFactor + GRWJC;%%%JC OUTPUT

%Calculates the Left Hand CoM
%Inputs: GRHC, GRWJC
%*****

LHandCentre = (GLHC - GLWJC)*LForearmFactor + GLWJC;%%%JC OUTPUT

%Calculates the Right Thigh CoM
%Inputs: GRKJC, GRAJC
%*****

RThighCentre = (GRAJC - GRKJC)*RThighFactor + GRKJC;%%%JC OUTPUT

%Calculates the Left Thigh CoM
%Inputs: GLKJC, GLAJC
%*****

LThighCentre = (GLAJC - GLKJC)*LThighFactor + GLKJC;%%%JC OUTPUT

%Calculates the Right Calf CoM
%Inputs: GRKJC, GRAJC
%*****

RCalfCentre = (GRAJC - GRKJC)*RCalfFactor + GRKJC;%%%JC OUTPUT

%Calculates the Left Calf CoM
%Inputs: GLKJC, GLAJC
%*****

LCalfCentre = (GLAJC - GLKJC)*LCalfFactor + GLKJC;%%%JC OUTPUT

%Calculates the Right Foot CoM
%Inputs: GRAJC, GRFoot
%*****

RFootCentre = (GRFoot - GRAJC)*RFootFactor + GRAJC;%%%JC OUTPUT

%Calculates the Left Foot CoM
%Inputs: GLAJC, GLFoot
%*****

LFootCentre = (GLFoot - GLAJC)*LFootFactor + GLAJC;%%%JC OUTPUT

%Determines the position of the Thorax Centre with an algorithm which seems
%totally off the wall!!!
%inputs: location of CURRENTC7 - not the marker - CURRENTC7True
% coordinates of the L5 - GLumbar5
%*****

GLumbar5;
CURRENTC7;
C74 = [1 CURRENTC7];
loC74 = InvThoraxTrans*transpose(C74);
loC7 = [loC74(2,1) loC74(3,1) loC74(4,1)];
loC7True = loC7 + [mm 0 0];
loC7True4 = [1 loC7True];
GC7True4 = ThoraxTrans*transpose(loC7True4);
GC7True = [GC7True4(2,1) GC7True4(3,1) GC7True4(4,1)];%%%JC OUTPUT
%loLumbar5 = InvThoraxTrans*GLumbar5;

GC7True2GLumbar5 = GLumbar5 - GC7True;

ThoraxCentre = 0.63*(GC7True2GLumbar5) + GC7True;%%%JC OUTPUT
%the thorax centre is found along the line from CURRENTC7 to L5
%and is scaled in that direction.

```

```

% BodyCoM = (PelvisWeighting*GPelCentre + RArmWeighting*RArmCentre + LArmWeighting*LArmCentre + LForearmWeighting*LForearmCentre + RForearmWeighting*RForearmCentre +
RCalfWeighting*RCalfCentre + LCalfWeighting*LCalfCentre + RLegWeighting*RThighCentre+ LLegWeighting*LThighCentre + RFootWeighting*RFootCentre + LFootWeighting*LFootCentre +
ThoraxWeighting*ThoraxCentre + HeadWeighting*HeadCentre + LHandWeighting*LHandCentre + RHandWeighting*RHandCentre);%%JC OUTPUT
BodyCoM = (HeadWeighting*HeadCentre + RArmWeighting*RArmCentre + LArmWeighting*LArmCentre + LForearmWeighting*LForearmCentre + RForearmWeighting*RForearmCentre +
LHandWeighting*LHandCentre + RHandWeighting*RHandCentre + RLegWeighting*RThighCentre+ LLegWeighting*LThighCentre + RCalfWeighting*RCalfCentre + LCalfWeighting*LCalfCentre +
RFootWeighting*RFootCentre + LFootWeighting*LFootCentre + ThoraxWeighting*ThoraxCentre );%%JC OUTPUT Pelvis taken out... PelvisWeighting*GPelCentre +

%*****
%*****
%*****END*****
%*****
%*****

```

Appendix 3.1. A copy of the internet web page showing the status of the review paper entitled: “The measurement of the human centre of mass location in ambulating persons; a review of its legacy and application”(chapter 2).

Submissions Being Processed for Author Warrick Mckinon

Page 1 of 1

Submissions Being Processed for Author Warrick Mckinon

Page: 1 of 1 (1 total submissions)

Display 10 results per page.

Action	Manuscript Number	Title	Initial Date Submitted	Status Date	Current Status
View Submission	GAIP0S-D-06-00355	The measurement of the human centre of mass location in ambulating persons; a review of its legacy and application	Nov 17, 2006	Dec 05, 2006	Under Review

Page: 1 of 1 (1 total submissions)

<< Author Main Menu

Appendix 3.2. A copy of the internet web page showing the status of the paper entitled “Adult male human whole body centre of mass location measurement: magnitude of differences between segmental kinematic estimations and direct suspension measurements” (chapter 5).

Submissions Being Processed for Author Warrick McKinon

Page: 1 of 1 (1 total submissions)

Display 10 results per page.

Action	Manuscript Number	Title	Initial Date Submitted	Status Date	Current Status
View Submission	BM-D-06-00644	Adult male human whole body centre of mass location measurement: magnitude of differences between segmental kinematic estimations and direct suspension measurements.	14 Nov 2006	18 Nov 2006	Under Review

Page: 1 of 1 (1 total submissions)

<< Author Main Menu

Page 1 of 1