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Manuscript Title

Is the instrumented-pointer method of calibrating anatomical landmarks in 3D motion analysis reliable?

Author names and affiliations:

Gwenllian Fflur Tawy[a]

Philip Rowe[a]

[a]University of Strathclyde

Affiliation address:

The Department of Biomedical Engineering,

University of Strathclyde,

Wolfson Centre,

106 Rottenrow,

Glasgow,

G4 0NW

United Kingdom

Author email addresses:

gwenllian.tawy@strath.ac.uk

philip.rowe@strath.ac.uk

Corresponding author:

Name: Gwenllian Fflur Tawy

Email addresses: gwenllian.tawy@strath.ac.uk or gwenllian.tawy@gmail.com

Telephone number: +44 7791184029

Work Address: The Department of Biomedical Engineering, University of Strathclyde, Wolfson Centre, 106 Rottenrow, Glasgow, G4 0NW, UK

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IS THE INSTRUMENTED-POINTER METHOD OF CALIBRATING ANATOMICAL LANDMARKS IN 3D MOTION ANALYSIS RELIABLE?

ABSTRACT

Instrumented-pointers are often used to calibrate anatomical landmarks in biomechanical analyses. However, little is known about the effect of altering the orientation of the pointer during calibration on the co-ordinates recorded. Incorrect positioning of a landmark influences the axes created, and thus the kinematic data recorded. This study aimed to investigate the reliability of the pointer method for anatomical calibration. Two points were drawn onto a fixed box to resemble knee joint epicondyles, then a custom-made pointer was used to define the positions of these landmarks in three-dimensions. Twenty different pointer-orientations were chosen, and the position of the pointer in each of these orientations was recorded 8 times. Euclidean distances between single points were calculated for both landmarks and compared statistically ($\alpha = 0.05$). Average Euclidean distances between all reconstructed points were 3.2±1.4mm (range: 0.3-7.1mm) for one landmark and 3.3±1.5mm (range: 0.3-7.9mm) for the other. The x- and y-co-ordinates recorded differed statistically when the pointer was moved about the X and Y axes (anterior/posterior and superior/inferior to landmark) ($p < 0.05$). No statistical differences were found between co-ordinates recorded when the pointer was moved around the Z axes ($p > 0.05$). ICC values for all co-ordinates were excellent, highlighting the reliability of the method (ICC > 0.90). These results support this method of anatomical calibration; however, we recommend that pointers be consistently held in a neutral oriented position (where the handle is not anterior, posterior, superior or inferior to the landmark) during calibration, to reduce the likelihood of calibration errors.

1. INTRODUCTION

The use of skin-surface reflective markers to represent bony anatomical landmarks has been described as inaccurate, unreliable, and time consuming (Alexander & Andriacchi, 2001; Baker., 2006; Benedetti *et al.,* 1998; Benoit *et al.,* 2006; Sholukha *et al.,* 2013).

One notable source of error is ‘soft tissue artefact’ (STA) (Baker, 2006; Leardini *et al.,* 2005; Peters *et al.,* 2010). STA is caused by the movement of a marker in relation to its underlying bony position (Cappozzo *et al.,* 1996; Leardini *et al.,* 2005). As the markers are often attached directly to skin, movement of the limb naturally causes the soft tissue (especially skin and fat) surrounding the bone to move (Baker, 2006; Cappozzo *et al.,* 1996). Consequently, the marker attached to the skin may move to a position where it no longer truly represent the position of the bony anatomical landmark. This error can be amplified if the marker is placed on clothing; especially if the clothing is loose-fitting (Baker., 2006; Benedetti *et al.*, 1998).

Placement errors translate to errors in kinematic and kinetic data as they affect the anatomical axes calculated from marker positions (Alexander & Andriacchi, 2001; Benoit *et al.,* 2006; Della Croce *et al.,* 2005).

An alternative method of calibration uses a pointer attached to a cluster of asymmetrical markers; an instrumented-pointer (Benedetti *et al.,* 1998; Cappozzo *et al.,* 1995). This method involves creating a local co-ordinate system from the markers on the pointer. This technique, known as C.A.S.T (calibrated anatomical systems technique), was introduced by Cappozzo and colleagues in 1995 (Cappozzo *et al.,* 1995). The C.A.S.T method has been successful in orthopaedic surgery to calculate the mechanical axis of the femur (Belvedere et al., 2011; Smith et al., 2014). It is also commonly used in biomechanical research (Besier *et al.,* 2003; Cappozzo *et al.,* 1995; Fantozzi *et al.,* 2003; Hagemeister *et al.,* 2005; Lin *et al.,* 2015, Remelius *et al.,* 2014).

Implementing a C.A.S.T is believed to have advantages over individual reflective markers stuck onto skin or tight clothing, such as reduced soft tissue artefact (depending on the type of cluster used and activity carried out) (Besier *et al.,* 2003). Preparation of an individual is also quicker and simpler (Benedetti *et al.,* 1998).

Despite these benefits, it is currently unknown whether the way in which the pointer is held against a landmark (its orientation) during calibration affects the co-ordinates recorded. Thus, this investigation aimed to determine whether changing the orientation of the pointer significantly influences the 3D-position of two virtual landmarks used to create an axis. This investigation could therefore be used to identify pointer orientations which should be avoided during anatomical landmark calibration.

2. Methods

2.1. Pointer Development

A pointer with 4 fixed retro-reflective markers was created then labelled as a cluster in Vicon Tracker software (ver.2.2, Vicon Motion Systems, Oxford). A local co-ordinate system was created within the pointer using this software. A temporary marker (without its base of support) was used to determine the position of the pointer tip relative to the fixed markers on the pointer. This information was used to calculate the position of a virtual point (representing the tip of the pointer) into the local co - ordinate system of the wand. Marker width was taken into consideration in these calculations.

A custom-written function in D-Flow saved the three-dimensional positions of the pointer-tip (Motekforce Link, Amsterdam).

2.2. Recording Pointer Co-Ordinates

To replicate the positions of anatomical landmarks (e.g. lateral and medial knee epicondyles), two red dots were drawn onto two sides of a sturdy box. The dots were placed half-way across the width of the box, and a couple of centimetres below the top of the box.

The box was placed onto a stool in the field of view of 8 Vicon Bonita B10 cameras (Vicon Motion Systems, Oxford). Elasticated straps attached the box to the stool to prevent movement.

Ten different types of pointer orientations were investigated. Each was analysed with the pointer parallel to the ground as well as perpendicular to the ground. Thus, twenty combinations were recorded for each landmark (Fig. 1). Fig. 2 shows examples of the orientations analysed.

x-, y- and z-co-ordinates of a landmark were recorded 8 times per orientation, completely removing the pointer from the box between recordings. Three-dimensional graphs of the mean vectors produced between the two points per orientation type were generated with Matlab® (ver. R2014a: Mathworks Natick, MA). The x-axis was anteroposterior, the y-axis was vertical and the z-axis was mediolateral.

To confirm that the box did not move as the pointer was used against it, a marker was glued onto the box and the co-ordinates of the marker were recorded as the pointer was used twenty times (once for each orientation).

The cameras were calibrated as recommended by the manufacturers. The image error of each camera was <0.3mm (average camera error = 0.257mm).

2.3. Analysis of Data

Statistical analyses were carried out in Minitab software (ver. 16: Minitab Inc., State College, PA, USA). Intra-class correlation coefficients (ICCs) were determined per Shrout & Fleiss' schema (1979). The level of significance was set at $\alpha = 0.05$.

Euclidean distances between the recorded point and the mean of all recorded points for that landmark were calculated for both landmarks.

3. Results

Average Euclidean distance between reconstructed points were 3.2±1.4mm (range: 0.3-7.1mm) for the left-hand side of the box and 3.3±1.5mm (range: 0.3-7.9mm) for the right.

Greatest mean differences were between the points reconstructed when the pointer was positioned a) posteriorly with the short arm pointing posteriorly, and b) anteriorly with the short arm pointing anteriorly (7.1mm & 7.9mm for left and right landmarks). x- and y-co-ordinates recorded when the pointer was anterior to the landmark were significantly different to those recorded when it was posterior to the landmark ($p < 0.0001$ & $p = 0.002$, respectively). Co-ordinates recorded along the medio-lateral axis did not differ between these orientations ($p = 0.147$). The average Euclidean distance between points recorded with the pointer anterior to the landmark and posterior to it was 3.4mm.

x- and y-co-ordinates created when the pointer was superior to and inferior to the landmark differed statistically to one another ($p = 0.032$ & $p<0.0001$, respectively). Again, the z-co-ordinates were found to be similar (p = 0.083). The average Euclidean distance between points recorded with the pointer superior to the landmark and inferior to it was 2.3mm.

The smallest differences in Euclidean distances between points were observed when the pointer was rotated about the medio-lateral axis (0.3mm for both landmarks). No statistical differences were found: p = 0.055 for x-co-ordinates, p = 0.070 for y-co-ordinates and p = 0.944 for the z-co-ordinates.

ICC values of all co-ordinates recorded at both landmarks were excellent (all 0.99).

A 3D graph of the mean landmark positions recorded during each orientation was plotted to visualise the effect these mean values would have on the creation of an axis (Fig. 3). The magnitude and directions of these vectors changed as the orientation of the pointer changed (Fig. 3). Mean magnitude was greatest when the pointer was superior to the landmarks with the short arm pointing inferiorly (228.8mm). The smallest mean magnitude (214.6mm) was observed when the opposite orientation was assumed (giving a difference of 14.2mm), highlighting the effect of changing the orientation of the pointer during calibration. On average, moving the pointer from a superior to inferior orientation affected the magnitude of the vector by 1.7mm. When anterior and posterior orientations were adopted, the mean difference in magnitude was 0.4mm.

To determine the repeatability of a single point in a given orientation, each x-, y- and z-co-ordinate recorded per orientation were statistically compared. ICC values were 1.0000 for all twenty orientations.

4. Discussion

Locating an anatomical landmark incorrectly during the calibration stage of a gait assessment can directly affect the kinematics calculated (Baker, 2006; Osis *et al.,* 2016; Schwartz *et al.,* 2004).

Our results showed that the mean co-ordinates recorded per orientation could lead to the production of different axes, suggesting that the vector produced changed when the orientation of the pointer was not maintained. This in turn could directly affect kinematics.

Osis *et al.* (2016) found that changing the position of a retro-reflective marker by 10mm resulted in a 7.59° change in knee and ankle internal-external rotation angles and a 5.17° change in knee abduction-adduction rotation angles when running.

The greatest Euclidean distances between reconstructed landmarks in our investigation were 7.1mm and 7.9mm; considerably smaller than those reported by Della Croce *et al.* (1999). According to their study, differences of up to 25.0mm were recorded at some anatomical landmarks (smallest difference of 4.8mm), where differences were calculated as the root mean squared distance from the mean position. This difference is likely to be since the landmark was pre-defined in this study, and no palpation was required.

Although our differences were smaller, an error of approximately 8mm (our maximum) could increase the kinematic error by around 5° (Osis *et al.,* 2016). McGinley *et al.* (2009) stated that clinically acceptable errors were those <5°. This is a cumulative error, consequently minimising the likelihood of pointer related errors arising is paramount for an accurate calibration.

When the pointer was rotated about the anterior-posterior and vertical axes, the results recorded were statistically different for x- and y-co-ordinates. Difference between recorded z- co-ordinates may not have reached statistical significance due to the rigid property of the box. Thus, changing the position of the pointer along these axes should be avoided during calibration, as the error may be even greater when used on skin.

We are confident that the differences highlighted in our results were not due to movement of the box as the pointer was used against it, as y- and z-co-ordinates of a marker glued onto the box remained the same to 3 decimal places as the pointer was used. On occasion, the x-co-ordinate of the landmark became reduced by 0.001mm; otherwise the position was consistent.

The pointer should therefore be held in a neutral position with relation to the landmark when calibrating (i.e. not above, below, posterior or anterior to the landmark). Rotating the pointer about the medio-lateral axis did not have a significant effect on the co-ordinates recorded. Consequently, the pointer could be held in any orientation in this plane when calibrating.

The co-ordinates recorded were highly repeatable and reliable when a particular orientation was used (ICCs = 1.000). This highlights the importance of a consistent calibration technique, suggesting that using a combination of orientations, even about the medio-lateral axis, could be detrimental to the calibration process.

A limitation to this study is that there was no baseline co-ordinate against which the recorded co-ordinates could be compared, but this replicates the clinical situation where the true value is unknown. Furthermore, only one pointer was used in this study.

5. Conclusion

Despite the increase in use of instrumented-pointers in biomechanical research and orthopaedics to calibrate the 3D position of bony anatomical landmarks, no study to date had investigated the effect of pointer-orientation on the co-ordinates recorded.

Our results showed that the co-ordinates recorded by the pointer differed to a level which could influence kinematic reconstruction. The greatest Euclidean distance between reconstructed landmarks in our investigation was 7.9mm which could have led to a kinematic error of approximately 5°. Errors above 5° are clinically unacceptable. We therefore recommend that the pointer should be consistently held in a neutral position to the landmark (i.e. not inferior, superior, anterior or posterior to the landmark) during anatomical calibration to reduce the chances of introducing error through improper pointer orientation.

Overall, we are confident that the pointer-calibration method can be reliably used to record the position of an anatomical landmark in three dimensions. However, accurate location of the anatomical landmark by palpation is still necessary, regardless of whether a pointer or static marker is used to record its location on the body.

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Conflict of Interest Statement

We have no conflict of interest to declare.

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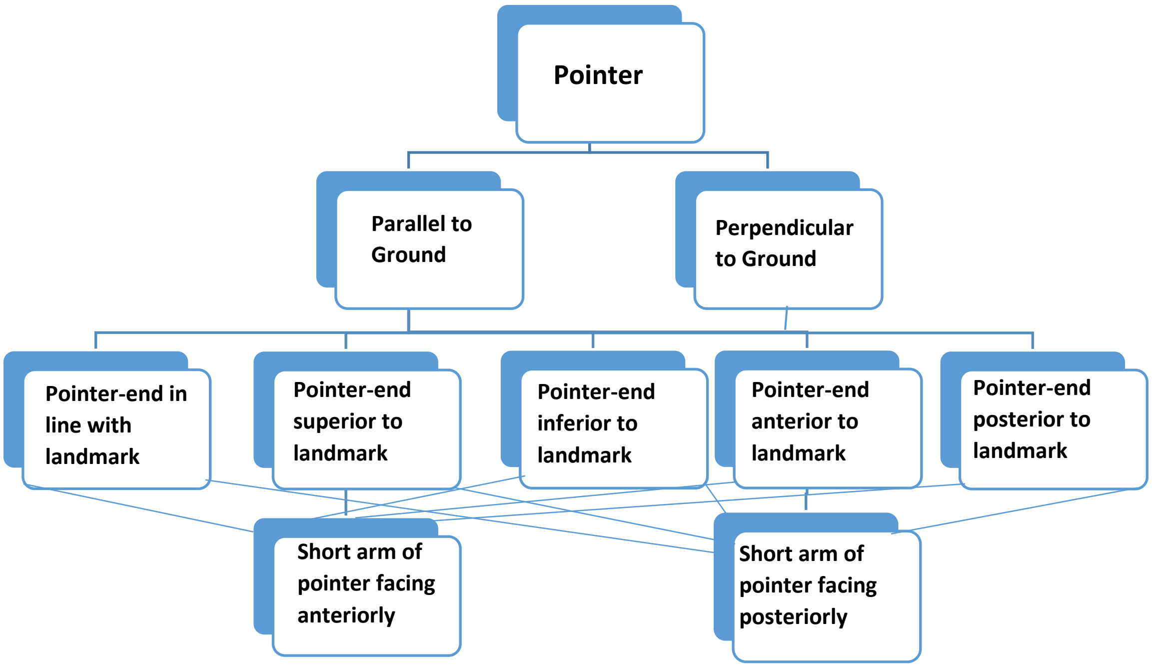

Figure 1: Twenty combinations of pointer orientations used to investigate the effect of orientation on the landmark co-ordinates recorded.

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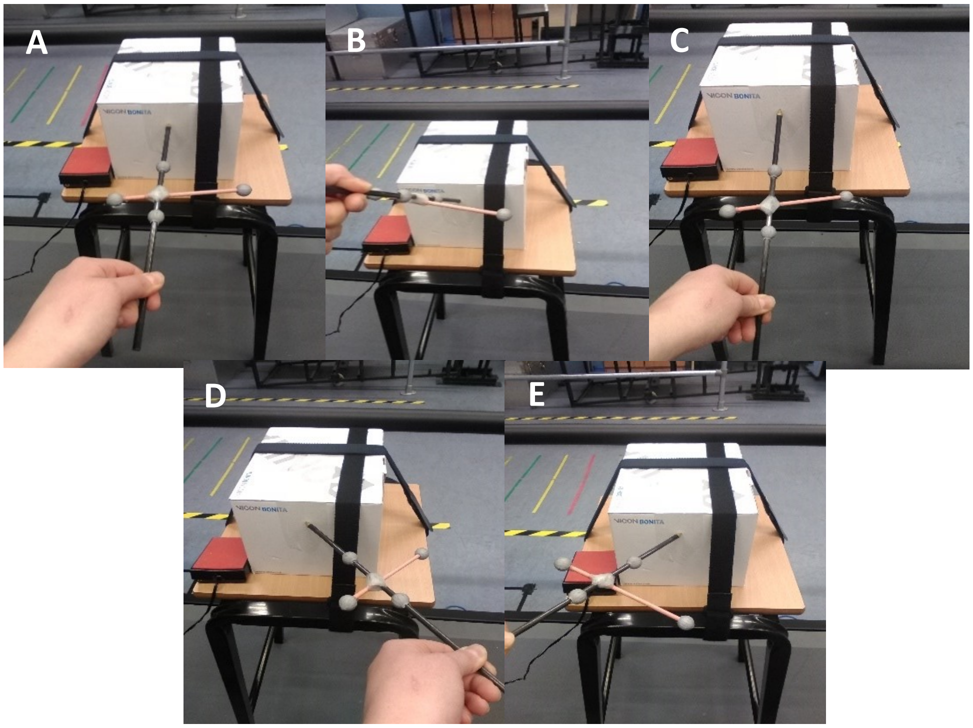

Figure 2: Examples of 5 pointer orientations investigated in this study. In all cases the pointer is parallel to the ground. The pointer-end is A: in line with the landmark, B: superior to the landmark, C: Inferior to the landmark, D: Posterior to the landmark, E: Anterior to the landmark.

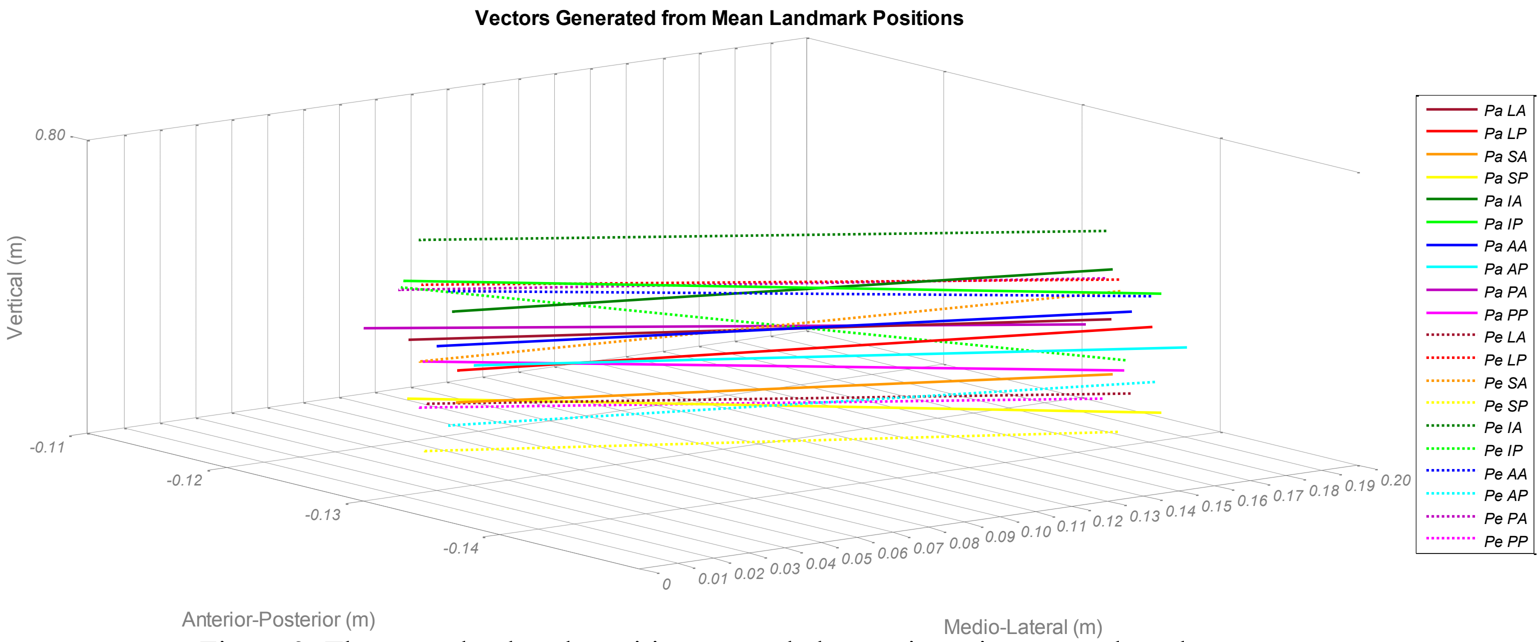

Figure 3: The mean landmark positions recorded per orientation were plotted as vectors to show the way in which pointer orientation would affect the creation of an axis. Pa = Parallel, Pe = Perpendicular, L = in-line with landmark, S = superior to landmark, I = inferior to landmark, A = Anterior to landmark, P = posterior to landmark, Ant = short arm of pointer orientated anteriorly, Pos = short arm of pointer orientated posteriorly.