

Can the reliability of three-dimensional running kinematics be improved using functional joint methodology?

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ABSTRACT

Traditional three-dimensional gait analyses require the skilled palpation of anatomical landmarks to identify joint parameters and produce reliable joint kinematics. Functional methods have been developed to help improve the reliability and validity of identifying joint kinematic parameters. The purpose of this study was to investigate whether a functional method could improve the between-day reliability of joint kinematics during running compared to a traditional manual marker placement method. It was hypothesised that the functional technique would result in greater within- and between-tester reliability. An eight-camera motion analysis system was used to evaluate the reliability of 3D lower extremity kinematics during running for both a functional and a manual marker placement technique. Reliability of the waveform shape, amplitude and offset of the kinematic curves was assessed using the coefficient of multiple correlation, range of motion and root mean square error respectively. The functional joint methodology did not improve the within- and between-tester reliability in terms of kinematic curve shape, amplitude or offset compared to the manual placement technique. When experienced examiners are used to place the anatomical markers together with a lean subject sample, functional methods may not improve the day-to-day reliability of three-dimensional gait kinematics over traditional marker placement techniques.

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1. Introduction

Three-dimensional (3D) gait analyses are commonly used in biomechanical and clinical movement research to both understand pathological movement patterns [1,2] and to assess whether interventions aimed at correcting gait anomalies are successful [3,4]. The majority of 3D motion capture techniques require the skilled palpation of anatomical landmarks to create meaningful, and repeatable, segmental anatomical co-ordinate systems (ACS) [5]. However, it is difficult to place anatomical markers in exactly the same location during any two separate testing sessions [6]. Such errors in marker placement may alter the orientation of segment ACS, resulting in subsequent differences in the joint kinematic curves during gait [5]. This is of particular importance in repeated measure studies, where differences in joint kinematics following an intervention may be masked by the errors associated with anatomical marker placements [7].

Recently, researchers have begun using functional methods to calculate joint centres [8–11]. While functional techniques have been proven reliable and valid in determining the hip joint centre [8–11], a method developed by Schwartz and Rozumalski [11] allowed the calculation of a joint centre of rotation (CoR) in joints with multiple degrees of freedom, as well as an average axis of rotation (AoR) in hinge-like joints. This resulted in a functional technique that could be applied to compute both hip and knee parameters in a clinical setting. Since functional methods reduce the reliance on manual marker placement to create segmental ACSs, they could be particularly useful in repeated measure studies examining joint kinematics. Functional approaches may also be superior in experimental setups where different testers are required to place the anatomical markers. Besier et al. [8] reported slight improvements in hip and knee joint kinematic repeatability during walking when functional methods were used in comparison to manually identified landmarks. However, to the authors' knowledge, no studies have investigated whether functional methods improve the reliability of joint kinematic data during running.

Reliability data from gait studies are often reported as indices such as correlation coefficients [12–14]. Few studies report the reliability of gait analysis techniques in terms of absolute errors in

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degrees [7,15], making it difficult to decide whether the measurement techniques are of sufficient precision to detect clinical changes in gait. Therefore, measures of reliability that are more directly related to the kinematic variables of interest are needed for 3D gait analyses [7,15].

In summary, the application of functional methods in creating segmental ACSs may prove valuable in reducing the errors in running gait analyses associated with the manual palpation of anatomical landmarks. Therefore, the purpose was to compare within- and between-tester reliability of between-day lower extremity joint kinematic data during running for a manual palpation model (MAN) and a functional model (FUN). It was hypothesised that FUN would demonstrate improved within- and between-tester reliability compared to MAN. Traditional reliability indices as well as absolute measures of difference (offsets) were used for comparison.

2. Methods

2.1. Subjects

Ten (seven females, three males) healthy runners (age = 27 ± 8 years; mass = 66.2 ± 7.7 kg; height = 1.68 ± 0.10 m; BMI = 23.5 ± 2.0) participated in this study. All subjects provided informed consent prior to participation. Subjects visited the laboratory on three occasions separated by a minimum of two days. During each session, subjects underwent a 3D gait data collection. Two testers (1 and 2) performed the data collections. Subjects were seen by tester 1 on the first and second visits, and by tester 2 on the third visit.

2.2. Experimental protocol

For the gait analysis, 9 mm diameter retro-reflective spherical markers were placed on the right leg unless stated (Fig. 1). Anatomical markers were placed on the following landmarks: first and fifth metatarsal heads; medial and lateral malleoli; medial and lateral femoral condyles; greater trochanter (bilateral); anterior superior iliac spine (ASIS) (bilateral); iliac crest (bilateral). For tracking motion trials, technical marker clusters were placed on the pelvis, thigh and shank. A rigid shell with three markers was placed over the sacrum with the two superior markers at the level of the posterior superior iliac spines (PSIS), and rigid shells with four markers were attached to shank and thigh. Technical markers for the foot were placed on the posterior aspect of the shoe: two markers were positioned to be vertically aligned on the posterior heel counter with a third marker placed laterally. All subjects wore standard laboratory shoes (Nike Air Pegasus, Nike Inc., USA) during testing.

Eight Vicon cameras (Vicon, Oxford, UK) collected marker co-ordinate data at 200 Hz. Based on residual analysis, three-dimensional co-ordinate data were filtered at 10 Hz using a fourth order Butterworth filter [16]. Prior to the motion trials, a standing calibration trial was collected. Subjects assumed a standardised stance with their feet positioned on two parallel lines 0.3 m apart. Following the standing trial, the subjects performed separate functional movement trials for the hip and knee. The subject performed each functional movement in a smooth, continuous motion with minimal movement in joints other than the one of interest. The hip joint trial consisted of performing the following motions twice: hip flexion, abduction, and circumduction [10,17]. Subjects were instructed to keep the range of motion at the hip joint to approximately 30° . The knee joint trial consisted of five smooth flexion-extension cycles, ranging from full extension to approximately 90° of flexion [8,11]. The subject stood on the contralateral leg and flexed the ipsilateral hip slightly allowing the foot to clear the ground during the movement.

Upon completion of the functional movement trials, the anatomical landmarks were removed and subjects ran on a treadmill at 2.7 m/s. Kinematic data for five complete footfalls of the right limb were collected following a 3-min treadmill running accommodation period to enable the subject to achieve their natural running style [18].

2.3. Definition of joint centres and co-ordinate systems

Two custom models (MAN and FUN) were created using Visual 3D software (C-Motion Inc., Germantown, USA). Anatomical (ACS) and technical co-ordinate systems (TCS) were defined for the pelvis, thigh, shank and foot. The technical co-ordinate system (TCS) was defined for each segment using the technical marker clusters placed on that segment. The joint centres and thus the segment ACSs were defined relative to the TCS during the standing calibration trial. However, the methods used to determine the hip and knee joint centres, together with the definition of the thigh and tibial ACSs differed between the MAN and FUN models.

For the MAN model, the hip joint centre was predicted based on the inter-ASIS breadth using the methods described by Bell et al. [19]. This method placed the hip

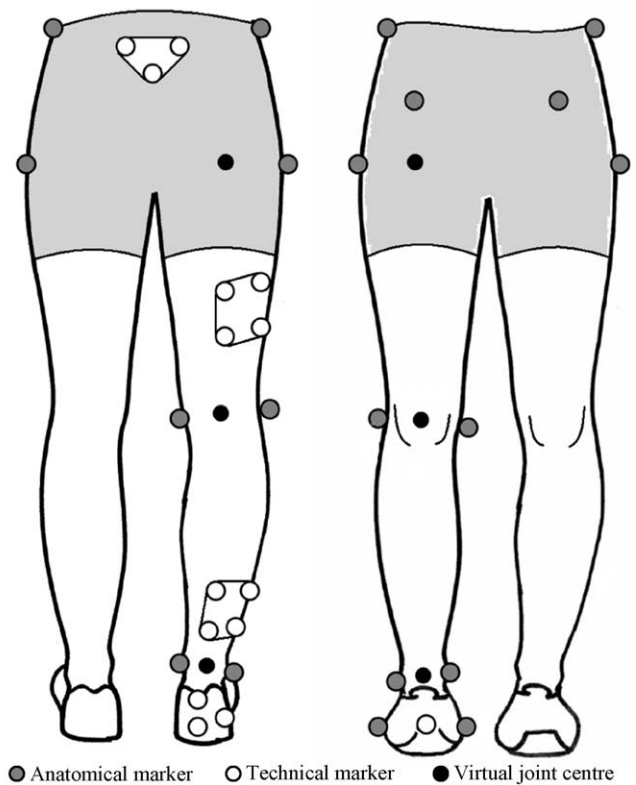


Fig. 1. Placement of the reflective markers on the lower extremity. Anatomical markers were used to create segmental ACSs while the technical clusters were used for tracking purposes during the dynamic movement trials. Virtual joint centres were created at the hip, knee and ankle.

joint centre 14% of the ASIS breadth medially, 19% posteriorly, and 30% distally from the ipsilateral ASIS. The knee joint centre was defined as the midpoint between the medial and lateral markers placed on the femoral condyles. The FUN model used functional methods based on Schwartz and Rozumalski [11]. Briefly, the calculation used rotations between two rigid segments to calculate an instantaneous AoR between each pair of time points. The average intersection point of these AoRs gives an approximate CoR, which is then called the joint centre. However, given that the knee joint has a large range of motion just in the sagittal plane, functional methods were expected to only give a reliable AoR. Therefore, to define the knee joint centre, the medial and lateral knee markers were projected into the AoR for the knee joint, and the joint centre was defined as the midpoint between these two projected landmarks [8]. The ankle joint centre was defined the same way for both MAN and FUN methods as the midpoint between the medial and lateral malleoli.

The pelvis ACS was defined the same way for both MAN and FUN models. The vertical axis (y) was the line joining the midpoint of the iliac crest markers and the midpoint of the greater trochanters with its positive direction proximal. The antero-posterior axis (x) was orthogonal to the frontal plane defined by the iliac crest and greater trochanter markers with its positive direction anterior. The medio-lateral axis (z) was the cross-product of the x - and y -axes with its positive direction to the right.

The y -axis of the thigh ACS in both models was oriented as the line joining the hip and knee joint centre with its positive direction proximal. The x -axis was orthogonal to the frontal plane with its positive direction anterior. For the MAN model the frontal plane was formed by the lateral epicondyle, hip and knee joint centre whereas both joint centres and the knee AoR were used in the FUN model. The z -axis was then defined as the cross-product of x - and y -axes with its positive direction lateral.

The shank and foot ACSs were defined identically for both MAN and FUN models. The y -axis of the shank ACS was the line passing from the ankle joint to the knee joint centre. The x -axis was orthogonal to the plane defined by the lateral malleoli, ankle and knee joint centre with its positive direction anterior. The z -axis was the cross-product of the x - and y -axes with its positive direction lateral. For the foot ACS, the y -axis was defined as the line joining the distal and proximal posterior heel markers with its positive direction proximal. The x -axis was parallel to the floor and ran from the distal posterior heel marker through the midpoint of the first and fifth metatarsal heads. The z -axis was the cross-product of the x - and y -axes with its positive direction lateral.

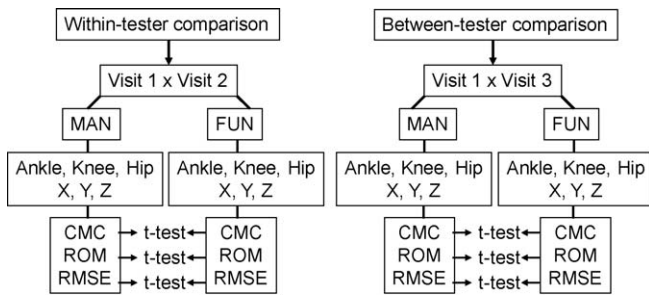


Fig. 2. Schematic of the experimental design and statistical testing protocol.

2.4. Data processing

Visual 3D software was used for filtering co-ordinate data, the identification of functional joint centres/axes of rotation, and joint angle calculations. Cardan angles were used to calculate the 3D joint angles of the hip, knee and ankle joints. All joint angles were referenced as the distal segment relative to the proximal segment with the cardan angle sequence of rotations following a z–x–y convention. Joint angle kinematics were analysed for the stance phase and normalised to 101 data points. To determine the stance phase, initial contact (IC) and toe off (TO) were identified using a velocity-based algorithm applied to the posterior distal heel and peak knee extension respectively [20].

2.5. Data analysis

To compare the between-day reliability of running joint kinematics derived from FUN and MAN techniques, three reliability variables that compared different aspects of the between-day kinematic curves were selected. To compare the overall shape of the kinematic waveform patterns (MAN vs FUN), the coefficient of multiple correlation (CMC) was calculated with the average value subtracted from each curve [13]. Differences in the amplitude of the kinematic curves (MAN vs FUN) were estimated by comparing the overall range of motion (ROM) of the curve. ROM was calculated as the maximum minus the minimum value. Errors due to kinematic offsets were assessed by calculating the average root mean square error (RMSE) between the two curves (MAN vs FUN) [15]. Both within- and between-tester reliability variables (CMC, ROM, and RMSE) were compared independently for the MAN and FUN method (Fig. 2). The within-tester comparison of the FUN and MAN methods was conducted using reliability variables calculated between visits 1 and 2, while between-tester reliability was assessed using visits 1 and 3. Repeated measures *t*-tests were used to compare the reliability variables of the MAN and FUN methods. Significance was set at a level of $P < 0.05$ and all statistical analyses were undertaken using SPSS 15.0 (SPSS Inc., Chicago, USA).

3. Results

The between-day RMS errors revealed no major differences between the MAN and FUN methods (Fig. 3). The largest discrepancy in RMSE reliability between the MAN and FUN methods was 1.4° which was found for between-tester knee flexion/extension ($P = 0.08$).

The mean and standard deviation (SD) of the CMCs for the kinematic curves are shown in Table 1. Good reliability (CMC > 0.803) was found for both MAN and FUN methods. In

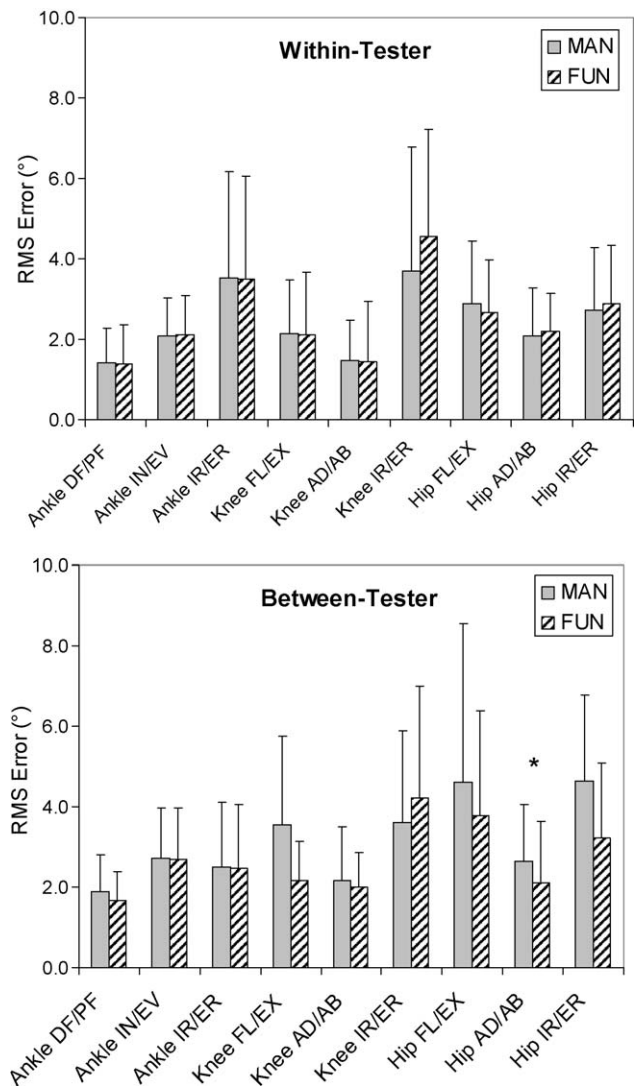


Fig. 3. Ensemble average RMS errors (SD) are shown for all subjects. Both within- (top) and between-tester reliability are illustrated.

general, the FUN method did not demonstrate greater within- or between-tester CMC values compared to MAN. The greatest difference in CMC between the MAN and FUN methods was only 0.082 and was found for between-tester knee adduction/abduction ($P = 0.31$).

The mean (SD) differences in joint angular ROM reliability between the MAN and FUN methods are presented in Table 2. There was only one statistically significant difference between the

Table 1 Mean (SD) within- and between-tester CMC values for both MAN and FUN methods.

	Within-tester		Between-tester	
	MAN	FUN	MAN	FUN
Hip FL/EX	0.998 (0.002)	0.997 (0.002)	0.998 (0.001)	0.998 (0.002)
Hip AD/AB	0.979 (0.017)	0.982 (0.015)	0.958 (0.049)	0.961 (0.045)
Hip IR/ER	0.913 (0.162)	0.914 (0.160)	0.950 (0.034)	0.949 (0.033)
Knee FL/EX	0.998 (0.002)	0.998 (0.002)	0.995 (0.005)	0.996 (0.005)
Knee AD/AB	0.924 (0.067)	0.960 (0.041)	0.885 (0.084)	0.803 (0.225)
Knee IR/ER	0.946 (0.048)	0.925 (0.091)	0.915 (0.137)	0.908 (0.117)
Ankle DF/PF	0.997 (0.004)	0.997 (0.003)	0.993 (0.007)	0.994 (0.006)
Ankle IN/EV	0.969 (0.035)	0.970 (0.034)	0.972 (0.029)*	0.974 (0.028)
Ankle IR/ER	0.981 (0.020)	0.980 (0.021)	0.971 (0.027)	0.973 (0.026)

* Significant differences between the MAN and FUN model ($P < 0.05$).

Table 2
Mean (SD) within- and between-tester ROM differences for both MAN and FUN methods.

	Within-tester difference (°)		Between-tester (°)	
	MAN	FUN	MAN	FUN
Hip FL/EX	3.0 (2.2)	3.1 (2.1)	1.9 (1.5)	2.0 (1.6)
Hip AD/AB	1.2 (0.9)	1.3 (0.9)	1.8 (2.0)	1.8 (2.0)
Hip IR/ER	2.2 (1.2)	2.1 (1.2)	2.6 (2.0)	2.6 (2.0)
Knee FL/EX	1.4 (1.2)	1.3 (1.1)	2.1 (1.3)	2.2 (1.5)
Knee AD/AB	1.3 (0.6)	1.1 (0.8)	1.9 (1.3)	1.2 (0.8)
Knee IR/ER	1.1 (0.9)	1.3 (1.1)	1.7 (1.3)*	1.0 (0.8)
Ankle DF/PF	1.4 (1.0)	1.2 (0.9)	2.4 (1.7)	2.2 (1.7)
Ankle IN/EV	1.1 (1.0)	1.1 (1.0)	1.5 (1.1)	1.5 (1.1)
Ankle IR/ER	0.5 (0.5)	0.4 (0.5)	1.6 (1.2)	1.6 (1.2)

* Significant differences between the MAN and FUN model ($P < 0.05$).

ROM reliability of the MAN and FUN methods which was found for between-tester knee internal/external rotation ($P = 0.03$). There were no other differences found between the MAN and FUN methods for either within- or between-tester ROM reliability variables.

4. Discussion

The purpose of this study was to compare the reliability of lower extremity running kinematic data collected using two different methods. It was hypothesised that the FUN method would improve both within- and between-tester reliability, compared to the typical anatomical landmark method (MAN). However, the results of this investigation suggest that there were no notable differences between the two methods in terms of reliability.

Both the FUN and MAN methods demonstrated highly repeatable kinematic waveform shapes, as evidenced by CMCs in excess of 0.803. The CMCs reported in the present study are higher than those reported previously for running [21] and walking [8,13,14]. A possible explanation may be that subjects ran on a treadmill in the present study as opposed to running overground. It has been demonstrated that treadmill gait results in reduced locomotor variability of the lower extremity joints compared to overground gait [22]. It is likely that treadmill running would reduce variability by imposing a constant speed, constraining side-to-side motion, and eliminating ‘targeting’ errors associated with the simultaneous acquisition of force plate data.

The within- and between-tester reliability of joint angular ROM was found to be within 3° for both FUN and MAN methods. There were no substantial differences in reliability between the two methods, with the only statistically significant difference being of a magnitude of less than 0.7° (knee IR/ER). Along with the similar between-day CMC values, one can conclude that both the shape and amplitude of the kinematic curves were similar between separate gait sessions regardless of the technique that was used to define the ACS. Interestingly, although the RMS errors were also similar between the MAN and FUN methods, the day-to-day differences for the RMS errors were typically greater than the ROM differences. For example, the between-tester differences for either technique ranged from 0.4° to 3.1° for ROM but 1.7° to 4.6° for RMS error. Given that the RMS errors indicate the average offset in the kinematic curves, these findings suggest that joint angular excursions and curve patterns may be obtained more reliably than values taken at discrete points of the curve (e.g. peak value). This supports the conclusions of Ferber et al. [12] who reported greater between-day reliability for joint angular excursions and velocities compared to absolute peak angle measures.

Although it was hypothesised that the FUN model would produce greater between-day reliability, the data suggest no improvement in kinematic waveform shape, amplitude or offset reliability measurements compared to the MAN technique. This is in agreement with Besier et al. [8] who reported that out of nine kinematic waveforms, the FUN model only improved the reliability for the frontal plane knee angle compared to manual landmark placement methods. Besier et al. [8] proposed that the experience of the tester placing the markers and the leanness of the study participants may have contributed to the similarities between the two techniques. Both testers used in the present investigation were well practiced in anatomical landmark palpation, having 4 and 7 years of experience conducting gait analyses respectively. The subjects used in the present study were also active runners with a low percentage body fat making the palpation of bony landmarks simpler than if an overweight population had been used.

A limitation of the present study was that between-tester reliability was not assessed during the same visit. Hence, the additional between-day variance would have influenced the between-tester variance due to measurement on separate days. A between-day design was used to assess both within- and between-tester reliability since it was believed this would better represent a real life clinical situation, where repeated measures 3D gait analyses are typically conducted on separate days to quantify a clinical outcome.

It could be argued that markers placed on the iliac crests and greater trochanters may not be the most reliable method to define the frontal plane of the pelvis and thus transverse plane hip kinematics. The decision to use this convention was based on the fact that a rigid shell was placed over the PSIS, making it awkward to use the more traditional ASIS and PSIS method to define the pelvis co-ordinate system. However, given that an identical pelvis model was used for both the MAN and FUN methods, this should not have biased the comparison of reliability.

It is possible that soft tissue artefact (STA) would have influenced the day-to-day kinematics curves derived using both MAN and FUN methods. The implementation of methods to tackle STA during functional movements may improve accuracy in predicting joint centres [23]. However, it has been suggested that the largest amount of ‘kinematic noise’ introduced by skin markers is a result of underlying muscle firing and the inertial effects of heel impact [23], which would be greater in running compared to the functional movements. Therefore, attempts to cope with STA during the functional movements might be negated by the STA evident during the running trials. Additionally, STA would have impacted the running kinematics calculated using both the MAN and FUN methods to a similar degree. In vivo studies are needed to establish which external marker techniques offer the most valid representation of skeletal joint kinematics during running.

It is worthy to note that only one functional technique was compared to the manual palpation method in this study. Several functional techniques exist in the literature that may perform with slightly differing degrees of reliability and validity in vitro [9,24]. Future research assessing the reliability and validity of different functional techniques in vivo is needed. Moreover, the nature of the movement pattern used to determine the functional joint parameters may also be of importance [17]. Future work should focus on determining optimal functional movement patterns to improve the reliability of 3D gait analyses.

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Conflict of interest

There are no conflicts of interest.

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