MARKER REGISTRATION FOR INVERSE KINEMATIC MODELS OF THE UPPER LIMB: IMPORTANT CONSIDERATIONS FOR THE SPORT SCIENTIST

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The scaling of rigid-linked skeletal models is an important consideration for researchers looking to calculate joint angles via inverse kinematics (IK). It has been suggested (Dunne et al., 2013) that registering marker positions with known kinematics during scaling can improve the accuracy of IK derived lower limb joint angles during gait. The purpose of this manuscript was to determine if registering marker positions with known joint kinematics can improve the accuracy and reliability of time varying IK derived elbow flexion/extension (FE) estimates during cricket bowling. Registering marker positions and joint kinematics (MKR) resulted in improved accuracy than marker positions only (MR) (RMSE = 8.9° v 25.1°) when compared with known DK derived elbow angles. The inter-tester reliability of MKR model elbow extension range was also superior (ICC = 0.626 v 0.318).

KEY WORDS: cricket, statistical parametric mapping, accuracy, reliability.

INTRODUCTION: Inverse Kinematic (IK) analysis estimates participant joint angles by way of a rigid-link model and a least-squares minimisation between participant experimental markers and model markers. To mitigate the influence of soft-tissue artefact (STA), this method has been proposed as an alternative to the more common Direct Kinematic (DK) method (Lu et al., 1999), where joint centre locations and segments defined each frame by recorded kinematic marker positions. With no joint constraints, DK solutions result in apparent segment length fluctuation.

For IK joint angles to match the participant's movement, (i) model geometry must match the participant anthropometry (matching segment lengths) and (ii) model marker locations must match the experimental marker locations on the participant. What may not be apparent is that errors in initial model marker placement can result in downstream non-linear offsets in joint angle calculation. Therefore, appropriate mapping of model markers to match the experimental marker locations on the participant must be taken into account when performing IK analysis. The mapping of marker locations from the participant to the model is known as marker registration.

Dunne et al (2013) showed that typical user based registration methods resulted in decreased accuracy and reliability of joint angle estimates. By performing gait analysis on a robot, the authors were able to quantify registration based errors and evaluate a method for improving registration. The proposed method used known joint angles from a static trial to pose the model, and then relocated model markers to match the experimental marker positions from the same static trial. Though this registration approach yielded encouraging results, it is yet to be determined if it can be applied in human modelling to improve IK accuracy and reliability.

The primary aim of this study was to determine if marker registration with known kinematics improves the accuracy and reliability of elbow flexion/extension (FE) kinematics during cricket bowling (compared with registering marker position only). Accurate and reliable representation of joint angles during cricket bowling is of particular importance due the ramifications modelling errors may have on a player's career. A secondary aim was to determine if Root Mean Square Error (RMSE) between model marker and experimental participant marker positions is appropriate for the assessment of IK solutions for cricket bowling.

METHODS: A single right armed bowler (1.85 m, 70 kg) was randomly selected from a pre-existing motion capture dataset of international level cricket bowlers. The data consisted of

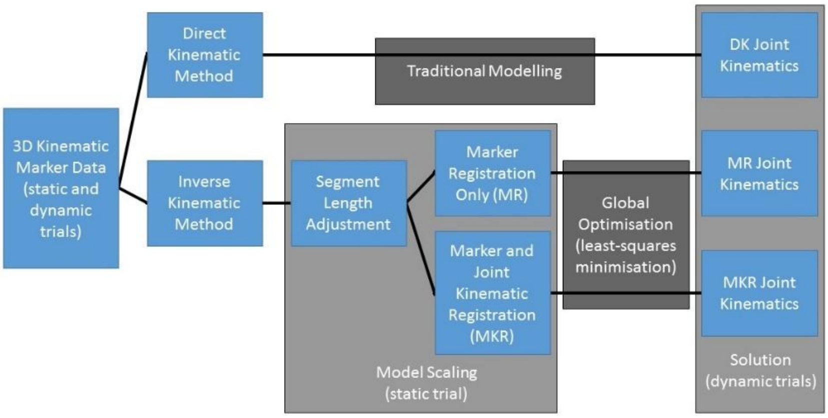

Figure 1: Representation of workflow for the proposed comparison study.

two experimental data recording sessions, collected by two independent investigators. During each session a single static trial and 12 dynamic cricket bowling trials were collected. The UWA upper limb kinematic marker set was applied (Campbell et al., 2009).

DK variables were calculated using Vicon Nexus (V1.8) software: joint centres and joint angles were calculated (Campbell et al., 2009) for all static and dynamic bowling trials. For this study, DK derived joint angles were considered the 'gold standard' in order to provide a measure of accuracy. It is acknowledged that DK is not a true gold standard measure, however it is currently the best form of motion capture for recording such large dynamic movements.

OpenSim 3.2 (Delp et al., 2007) was used to modify the Holzbaur Upper Limb Model (Holzbaur et al, 2005) and perform the IK analysis. The model was reduced to three segments (humerus, ulna, radius), two joints (elbow, radioulnar) and three degrees of freedom (elbow FE, elbow abduction/adduction, radioulnar pronation/supination). Model geometry was scaled according to participant joint centres calculated from the static trial using the DK approach (segment lengths adjusted). Two copies of the (now scaled) model were created (i) a version whereby the model markers were adjusted using the internal methods of OpenSim (registering marker positions only: MR) and (ii) a version where the model static joint angles were set to match those calculated using DK, then model markers were moved to match experimental marker locations (registering marker positions with known kinematics: MKR) (Dunne et al., 2013). After the final scaling process the assumed elbow joint angles were recorded.

IK was performed on all dynamic bowling trials using both MR and MKR models. Time varying elbow FE angles were output for each delivery between upper arm horizontal and ball release. Following IK, the mean RMSE between the model and experimental marker locations was reported by OpenSim and recorded for both models ($RMSE_{MARKER}$).

Time varying elbow FE waveforms were compared using $RMSE_{WAVEFORM}$ and one dimensional statistical parametric mapping (SPM1D) (Pataky et al., 2013) for: 1a) MR inter-tester repeatability, 1b) MKR inter-tester repeatability, 2a) MR accuracy (MR vs. DK), 2b) MKR accuracy (MKR vs. DK). Intra-class correlation (ICC) was calculated to compare elbow extension range (maximum elbow flexion minus minimum elbow flexion) between testers as a measure of each model's reliability.

RESULTS: The elbow angles estimates by MR during the scaling process were noticeably different from the DK joint angle estimates in both testing sessions (Table 1). MKR elbow

Table 1: Static joint angles post- scaling

		Elbow Angle (°)	
		Flexion	Abduction
1	MR	-9.3	20.0
	MKR (DK)	5.7	21.2
2	MR	-15.8	12.6
	MKR (DK)	5.1	19.3

Table 2: Elbow extension range (EER) averages (and standard deviations) and ICC for inter-tester reliability

EER	Session 1	Session 2	ICC
MR	30.2° *(± 2.9)*	29.7° *(± 18.3)*	0.318
MKR	33.1° *(± 3.7)*	37.4° *(± 3.8)*	0.626
DK	37.1° *(± 4.6)*	38.4° *(± 6.7)*	0.629

angles, defined by the DK calculated elbow angles, remained unchanged.

MKR inter-tester repeatability was affected by an offset in flexion values, but does demonstrate a similar waveform pattern (SPM1D: 95% of delivery phase significantly different; $RMSE_{WAVEFORM}$: 8.90°). MR inter-session repeatability is heavily affected by large variation in session two (SPM1D: 100% delivery phase significantly different; $RMSE_{WAVEFORM}$: 25.13°). Both models returned differences in time varying elbow FE angle when compared with the DK derived estimates (Figure 2). The $RMSE_{WAVEFORM}$ DK vs MKR model was much more comparable than the DK vs MR model (4.93°, 30.37°). Inter-tester reliability (Table 2) for MKR and DK modelling approaches were both moderate-high, while MR returned low inter-tester reliability. Both the MR and MKR models had similar average $RMSE_{MARKER}$ differences reported after IK was performed (0.022 m and 0.025 m respectively).

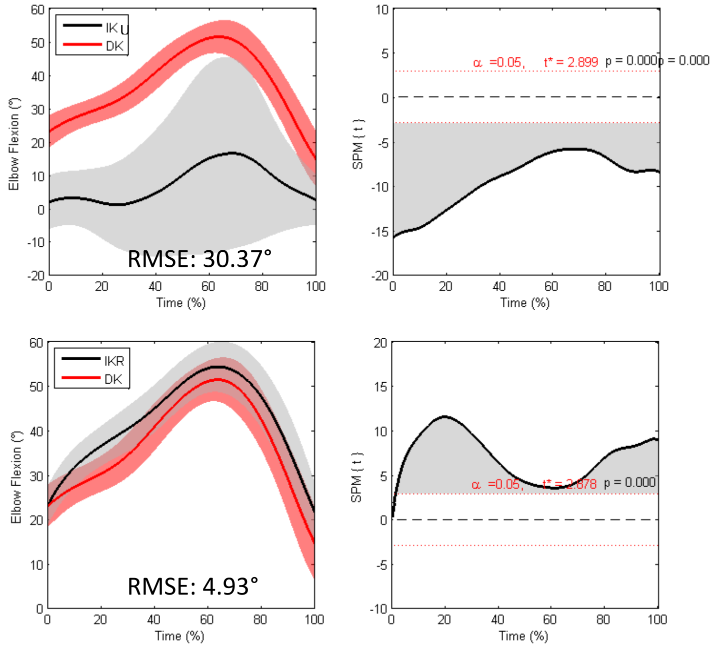

Figure 2: Accuracy measure - MR (top) and MKR (bottom) compared to the DK solution. Left graphs are ensembal averages from all trials ($RMSE_{WAVEFORM}$ inset); right is the SPM1D analysis, where any t statistic (black line) greater than the critical t-threshold (dotted line) indicates a significant difference (*p* value inset) between the two methods.

DISCUSSION: The aim of this study was to investigate whether registering marker positions with known kinematics improves the accuracy and reliability of IK calculations of elbow FE during cricket bowling. The combination did improve both the reliability and accuracy of IK solutions when compared with registering only marker positions, however differences did present when compared with traditional DK results.

Following the scaling process the MR model estimated the elbow as being hyperextended, whereas the DK derived angle estimates (and in turn MKR model estimates) had the elbow flexed. These initial differences in elbow FE estimates during the scaling process highlights that multiple kinematic solutions are possible during model marker registration. It appears that when initial model pose is not defined during the scaling process (MR), the global optimisation algorithm can choose any combination of joint angle permutations (within model constraints) (increase kinematic variability), with all variations fitting the model to the experimental data equally well. It is only when the initial model kinematics is defined that the model markers assume positions that more accurately represent experimental marker positions (reduced kinematic variability).

Assessment of the time varying elbow FE angles showed that when registering marker positions only (MR), the inter-tester repeatability was poor. This was in part due to the large inter-trial variability observed within each testing session, which was associated with the optimisation criterion used during IK. The optimisation is designed to minimise the error between the model's virtual marker positions and the experimental marker positions, with no consideration to the joint positions.

The DK calculated static elbow angles from both sessions show the static pose is highly repeatable, but as seen with the MR model, the variability in marker placement between testers may lead to different optimisation results and kinematic solutions (Table 1). An initial offset between the model marker positions and corresponding joint angles during scaling (seen in the MR model) likely contributed to the high inter-trial kinematic variability and the low

inter-tester repeatability. Given that with no pose definition the MR model assumed different elbow joint angles for each session during scaling, it is reasonable to assume that these initial differences lead to differences in IK solutions and resultant low inter-tester repeatability.
The inter-trial variability and inter-tester kinematic reliability of the MKR model improved substantially when compared with the MK model. During marker registration the MKR model markers and MR model markers both assume the same position in the global co-ordinate system, matching the experimental marker positions from the static trial. However, the location of each model marker within the anatomical co-ordinate system of the associated segment of each model is vastly improved when also registering with known kinematics. It is intuitive that, given the model markers are being moved to fit experimental marker positions from a static trial, the segment orientations/joint kinematics should also match the static trial, allowing for more anatomically accurate recreation of experimental marker positions within the model's anatomical co-ordinate systems. Despite this increase in anatomical relevance, SPM1D analysis showed that differences between testers, and with respect to DK results still exist. Future research is therefore recommended to improve the repeatability of IK derived upper limb kinematic solutions.
Interestingly, average $RMSE_{MARKER}$ differences between the model markers and experimental marker positions were almost identical whether using the MKR or MR model. This shows that $RMSE_{MARKER}$ should only be used to assess how well the model has fit the experimental data, and not to verify or validate a model's IK derived joint kinematic estimates.
As with all case studies, this study was limited as a single participant performed a single overhead movement (i.e. cricket bowling). Additionally, the use of DK derived elbow FE angles during the bowling action as a 'gold standard' to assess model accuracy was not ideal, but is the best method currently available. Nevertheless, this research shows that registering marker positions with known kinematics does improve the IK derived kinematics for cricket bowling. If proven repeatable, the MKR approach could be utilised as an alternative measure in the case of a bowler legality dispute, providing a secondary solution.

CONCLUSION: Registering marker position with known kinematics increases both the reliability and accuracy of IK derived elbow FE estimates during cricket bowling. For sport biomechanists considering which kinematic approach to use, we have shown that using IK to calculate elbow FE during cricket bowling is a viable option to DK - however, consideration needs to be taken during model scaling to ensure the most accurate and reliable results are obtained. Importantly, this includes defining initial elbow kinematics during marker registration. RMSE differences between model and experimental marker positions is not an appropriate assessment of IK derived joint kinematic estimates.

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