PRESCRIBING JOINT CO-ORDINATES DURING MODEL PREPARATION IN OPENSIM IMPROVES THE ACCURACY OF LOWER LIMB KINEMATICS

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The lower limb sidestepping kinematics of 20 elite female athletes were calculated using: 1) an established direct kinematic (DK) model (criterion) and, 2) two inverse kinematic (IK) models; one with and one without participant-specific joint co-ordinates prescribed during model preparation. The aim of this research was to determine whether prescribing joint co-ordinates influences the accuracy of IK derived sidestepping kinematics. Time-varying analysis (1D SPM) of IK derived hip, knee and ankle joint kinematics showed model's prepared with participant-specific joint co-ordinates more closely matched that of the criterion measure. Prescribing participant-specific joint co-ordinates during model preparation improves the accuracy of IK derived sidestepping kinematics in OpenSim.

KEY WORDS: inverse kinematics; IK; modelling; scaling; sport biomechanics; SPM.

INTRODUCTION: The specificity of a musculoskeletal model used to quantify human movement is one of the most important factors influencing the reliability of joint kinematic estimates. There are two principal categories of modelling approaches that can be used to estimate participant-specific kinematics; direct kinematic (DK) and inverse kinematic (IK) models. Although DK models are the most conventional in the field of biomechanics, it is well known they are greatly influenced by soft tissue artefact (STA) (Cappozzo, Catani, Leardini, Benedetti, & Della Croce, 1996) particularly during high velocity movements such as those experienced in sport (Fuller & Liu, 1997). More recently, IK models have gained popularity in the sport biomechanics literature for their theoretical potential to mitigate the influence of STA during high velocity sporting tasks. Though gaining popularity in the literature, there is a paucity of research directly comparing these modelling approaches (Kainz *et al.*, 2016), which may have significant impacts on one's clinical interpretations of motion capture data depending on the modelling approach used.

Recently, Kainz *et al.* (2016) measured lower limb kinematics of participants with cerebral palsy using a common Vicon Plug-in-Gait DK model as well as an IK modelling approach. During this assessment, kinematic differences of up to 13º were observed. Robinson, Donnelly, Tsao, & Vanrenterghem, (2014) have directly compared DK and IK derived kinematics during change of direction sporting tasks, with notable kinematic differences observed in non-sagittal hip, knee and ankle movements. When comparing their data to biplanar videoradiography published by Miranda, Rainbow, Crisco, & Fleming, (2013), Robinson *et al.* (2014), suggested that IK derived kinematics more closely align with the underlying bony motion of the thigh and tibia, which was attributed to IK being able to mitigate the influence of STA during the high velocity sidestepping tasks.

It is unclear from previous studies comparing DK and IK modelling approaches whether participant-specific co-ordinates were prescribed during the marker registration phase of model preparation. This is an important consideration that may have confounded the interpretation of results, as previous research has shown this step has a significant influence on the accuracy (Dunne *et al*., 2008) and repeatability (Wells, Alderson, Dunne, Elliott, & Donnelly, 2017) of lower and upper body kinematics. The purpose of this study was to determine what influence the prescription of participant-specific joint co-ordinates during the marker registration phase of model preparation (i.e., IK_{PC}) in OpenSim influences the accuracy of lower limb kinematic estimates during a clinically relevant unplanned sidestepping task. It is hypothesised that the IK_{PC} derived lower limb kinematics will be in closer agreement to the established DK model when compared with the IK derived kinematic estimates.

METHODS: Twenty elite female hockey players from the Australian Women's Hockey team (21.9±2.48 years, 1.68±0.08 m, 63.3±6.24 kg) attended one to four independent biomechanical data collection sessions. All participants were injury free and provided informed consent in accordance with the requirements of the UWA Human Research Ethics Board (RA/4/15333). In a randomised order, participants completed a series of pre-planned and unplanned straight-run, crossover-cut and sidestepping running tasks (Besier, Lloyd, Ackland, & Cochrane, 2001; Donnelly *et al*., 2012). Only unplanned sidesteps (UnSS) were used in analysis. Kinematics were recorded using a 22-camera Vicon MX/T40 system at 250Hz (Oxford Metrics, Oxford, UK) and force plate data at 2,000Hz (AMTI, Watertown, MA).

Three models driven by the same 3D experimental kinematic data were generated: 1) **DK** – an established DK model with functional hip and knee joint centres/axes (Besier, Sturnieks, Alderson, & Lloyd, 2003), 2) **IK** – model prepared without participant-specific joint co-ordinates during marker registration (Wells, Alderson, Dunne, Elliott, & Donnelly, 2017), 3) **IK_{PC}** – model prepared with participant-specific joint co-ordinates during marker registration (Wells *et al*., 2017). Time varying analyses of the scalar components was performed using one dimensional statistical parametric mapping (1D SPM; p<0.05 indicates significant difference) (Pataky, Robinson, & Vanrenterghem, 2013) and root mean square (RMS) errors. For simplicity, the mean RMS error and time varying kinematic differences for each joint decree of freedom of the hip and knee joint (flexion-extension, abduction-adduction, internal-external rotation) were calculated.

RESULTS: When lower limb kinematics from the inverse kinematic models were assessed against the DK model's estimates, time-varying SPM analysis showed a lesser degree of statistical difference between the DK versus IK_{PC} waveforms was 3-46% of stance (hip = 46.0±39.7%, RMS = 5.2±5.4°, p<0.001-0.040; knee = 56.3±31.2%, RMS = 6.7±4.2°, p<0.001-0.046; and ankle = 3%, RMS = 2.2°, p=0.044), compared with 46-100% of stance for the IK versus DK waveform comparison (hip = 69.7±52.5%, RMS = 14.1±11.1°, p<0.001-0.041; knee = 46.3±48.1%, RMS = 8.2±6.8°, p<0.001-0.038; and ankle = 100%, RMS = 10.9°, p<0.001) (Figure 1).

DISCUSSION: This study aimed to investigate two different inverse kinematic models prepared with (IK_{PC}) and without (IK) the prescription of participant-specific joint co-ordinates during the marker registration phase of model preparation (OpenSim), against an established, reliable DK model (Besier *et al.*, 2003). As hypothesised, the IK_{PC} model was in better kinematic agreement with the established DK model when compared to the IK model. The likely reason is because, prescribing participant specific joint co-ordinates defines the orientation of each joint degree of freedom relative to 0° during model scaling. This helps to reduce the magnitude kinematic offsets that may be introduced during the IK process. The joint degree of freedom most influenced by the prescribing participant-specific joint co-ordinates was hip joint flexion-extension; RMS errors relative to the DK model were reduced by 15°. Other joint degrees of freedom that became better aligned with the DK model when joint co-ordinates were prescribed included hip int-external rotation (RMSE: IK=23°, p<0.001 vs. IK_{PC}=11°, p<0.001), knee ab-adduction (RMSE: IK=15°, p<0.001 vs. IK_{PC}=9°, p<0.001) and ankle plantar-dorsiflexion (RMSE: IK=11°, p<0.001 vs. IK_{PC}=2°, p=0.044). Other joint degrees of freedom like hip ab-adduction (RMS: IK<2°, p=0.041 vs. IK_{PC}<2°, p=0.040), knee flexion-extension (RMS: IK<2°, p=0.038 vs. IK_{PC}<2°, p=0.006) and knee int-external rotation (RMS: IK<8, p=0.002° vs. IK_{PC}<9°, p=0.004) were relatively uninfluenced through the prescription of participant-specific co-ordinates during model preparation.

Although results illustrate the IK_{PC} model produced more consistent kinematics to the established DK model, for some joint degrees of freedom, both inverse kinematic models estimated very different joint kinematics. These joint degrees of freedom were hip int-external rotation, knee ab-adduction and to a lesser extent, knee int-external rotation.

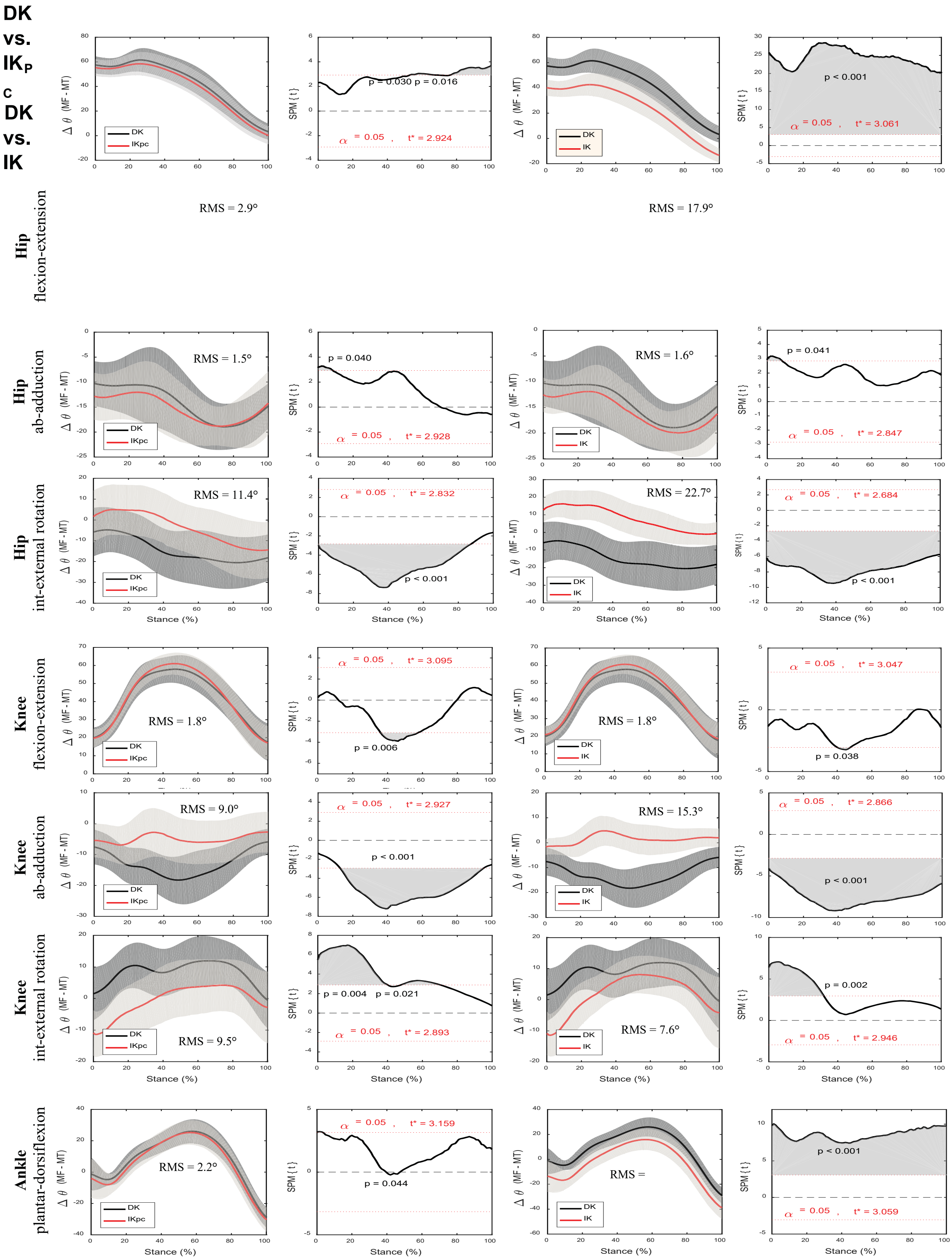
DK vs. IKpc
DK vs. IK
Hip flexion-extension
RMS = 2.9°
RMS = 17.9°
p = 0.030 p = 0.016
p < 0.001
α = 0.05 , t* = 2.924
α = 0.05 , t* = 3.061
Hip ab-adduction
RMS = 1.5°
RMS = 1.6°
p = 0.040
p = 0.041
α = 0.05 , t* = 2.928
α = 0.05 , t* = 2.847
Hip int-external rotation
RMS = 11.4°
RMS = 22.7°
α = 0.05 , t* = 2.832
α = 0.05 , t* = 2.684
p < 0.001
Knee flexion-extension
RMS = 1.8°
α = 0.05 , t* = 3.095
α = 0.05 , t* = 3.047
p = 0.006
p = 0.038
Knee ab-adduction
RMS = 9.0°
RMS = 15.3°
α = 0.05 , t* = 2.927
α = 0.05 , t* = 2.866
p < 0.001
Knee int-external rotation
RMS = 9.5°
RMS = 7.6°
p = 0.004 p = 0.021
p = 0.002
α = 0.05 , t* = 2.893
α = 0.05 , t* = 2.946
Ankle plantar-dorsiflexion
RMS = 2.2°
RMS =
α = 0.05 , t* = 3.159
α = 0.05 , t* = 3.059
p = 0.044
p < 0.001
Δ θ (MF - MT)
SPM{t}
Stance (%)
DK
IKpc
IK

Figure 1: Mean time normalised hip, knee and ankle joint angles (º) for IK_{PC} vs. DK (left) and IK vs. DK (right) comparisons. RMS errors between waveforms are imbedded within kinematic time series data. Shaded great areas above the t-statistic thresholds indicate significant kinematic differences between modelling approaches (*p*<0.05). All curves are time normalised over the stance phase (%).

These degrees of freedom have been shown to produce less repeatable kinematic estimates relative to other degrees of freedom in the past (Gorton, Herbert, & Goode, 2001), which is thought to be related to the presence of STA at the thigh. Specifically, the DK model stores anatomical information for definition of the thigh segment (i.e. the knee joint centre) within a thigh based technical co-ordinate system. Interestingly, results of this study are supported by biplanar videoradiography data by Miranda *et al.* (2013), which reported values of ±5° for peak knee ab-adduction during change of direction tasks.

In this study, the IK_{PC} kinematic estimates were similar to *in-vivo* kinematic estimates published by Miranda *et al.* (2013) suggesting that the prescription of participant specific joint co-ordinates during marker registration is an important consideration for obtaining biologically accurate frontal plane knee kinematics.

CONCLUSION: The prescription of participant specific joint co-ordinates during marker registration of model preparation in OpenSim is an important methodological consideration for biologically reasonable lower limb kinematics during high velocity unplanned sidestepping tasks.

REFERENCES:

Besier, T. F., Lloyd, D. G., Ackland, T. R., & Cochrane, J. L. (2001). Anticipatory effects on knee joint loading during running and cutting manoeuvres. *Medicine and Science in Sports and Exercise*, *33*(7), 1176–1181.

Besier, T. F., Sturnieks, D. L., Alderson, J. A., & Lloyd, D. G. (2003). Repeatability of gait data using a functional hip joint centre and a mean helical knee axis. *Journal of Biomechanics*, 36(8), 1159–1168.

Cappozzo, A., Catani, F., Leardini, A., Benedetti, M. G., & Della Croce, U. (1996). Position and orientation in space of bones during movement: experimental artefacts. *Clinical Biomechanics*, 11(2), 90–100.

Donnelly, C. J., Elliott, B. C., Ackland, T. R., Doyle, T. L. A., Besier, T. F., Finch, C. F., & Lloyd, D. G. (2012). An anterior cruciate ligament injury prevention framework: incorporating the recent evidence. *Research in Sports Medicine*, 20(3–4), 239–262.

Dunne, J., Besier, T. F., Lloyd, D. G., Lay, B., Delp, S. L., & Seth, A. (2008). Automated marker registration improves OpenSim joint angles and moment estimation of a humanoid robot. Presented at the XXIV Congress of the International Society of Biomechanics, Brazil.

Fuller, J., & Liu, L. J. (1997). A comparison of lower-extremity skeletal kinematics measured using skin- and pin-mounted markers. *Human Movement Science*, 16(2–3), 219–242.

Gorton, G., Herbert, D., & Goode, B. (2001). Assessment of the kinematic variability between 12 shriners motion analysis laboratories. *Gait & Posture*, *13*(2), 247.

Kainz, H., Modenese, L., Lloyd, D., Maine, S., Walsh, J., & Carty, C. (2016). Joint kinematic calculation based on clinical direct kinematic versus inverse kinematic gait models. *Journal of Biomechanics*. 49(9), 1658-1669.

Miranda, D. L., Rainbow, M. J., Crisco, J. J., & Fleming, B. C. (2013). Kinematic differences between optical motion capture and biplanar videoradiography during a jump-cut maneuver. *Journal of Biomechanics*, 46(3), 567–573.

Pataky, T. C., Robinson, M. A., & Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *Journal of Biomechanics*, 46(14), 2394–2401.

Robinson, M. A., Donnelly, C. J., Tsao, J., & Vanrenterghem, J. (2014). Impact of knee modeling approach on indicators and classification of anterior cruciate ligament injury risk. *Medicine and Science in Sports and Exercise*, 46(7), 1269–1276.

Wells, D., Alderson, J., Dunne, J., Elliott, B., & Donnelly, C. (2017). Prescribing Joint Co-ordinates during Model Preparation to Improve Inverse Kinematic Estimates of Elbow Joint Angles. *Journal of Biomechanics*, 51(25), 111–117.

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