PEAK MAGNITUDES OF DYNAMIC KNEE JOINT LOADING ARE NOT INFLUENCED BY CUSTOMISED BODY SEGMENT PARAMETERS.

Seokwon Lee, Mark Robinson, Scott Brennan and Mark Lake

RISES, John Moores University, Liverpool, U.K.

Although accurate body segment parameters (BSPs) do not appear to be important for peak joint moments recorded during walking, it is not clear whether joint moment magnitudes during highly dynamic activities can be modified when using individualised BSP data and having high frequency motion characteristics retained in the segmental acceleration data. Overall, it was found that BSPs had little influence on peak knee joint moment magnitudes during 45°cutting, drop jumping and fast running (even with high frequency signal components (up to 30 Hz) present in the dataset). This supports previous walking gait research that suggests BSPs have only a small effect on knee joint moment calculations.

KEYWORDS: knee joint moment, body segment parameters, 3D-printed tibio marker plate

INTRODUCTION: Knee motion and loading during locomotion has been evaluated using three-dimensional dynamic models of the lower limbs and pelvis and the determination of moments acting about the joint (Robinson and Vanrenterghem, 2012). Such loading estimates have been used in injury prevention (David et al., 2017) and rehabilitation (Kim and Eng, 2004). However, different components of the joint moment computations contain measurement errors, which include the estimation of body segment parameters (BSPs) (Ganley and Powers, 2004; Lee et al., 2009). Sensitivity analyses of measurement errors have been conducted mainly in the sagittal (flexion/extension) plane and during walking. For injury prevention and rehabilitation, accurate joint kinetics is also required in the transverse and frontal planes during highly dynamic sporting tasks.

BSPs are typically derived using cadaver-based data (Clauser et al., 1969 and Dempster, 1955) and geometrical modelling of body segments (Hanavan, 1964). However, recently, attempts have been made to determine individual customised BSPs using two-dimensional (2-D) projections of mass densities that have been measured by Dual energy X-ray absorptiometry (DEXA) (Ganley and Powers, 2004; Lee et al., 2009).

Therefore, the purpose of this paper is to examine whether the magnitude of knee joint moments during dynamic sporting actions can be influenced by having more accurate BSPs (determined using DEXA scanning) in combination with higher frequency motion characteristics of the movements being retained in the dataset.

METHODS: Dynamic motion trials (fast running, 45°cutting and landing with immediate jump) of 10 male (mean age = 24.4 ± 1.9 yr, height = 1.77 ± 0.07 m, mass = 77.6 ± 7.9 kg) and 8 female (mean age = 23.5 ± 1.5 yr, height = 1.70 ± 0.06 m, mass = 63 ± 6 kg) were collected. Twenty-two small reflective markers were placed on the subjects' skin for 3D motion capture purposes using the lower limb marker set from Robinson and Vanrenterghem (2012). Additionally, a tibio marker plate (TP) was tightly attached to the antero-medial aspect of the tibia on the dominant lower leg using non-stretch tape (see Figure 1). Participants' tibia were scanned by a 3D digital scanner for the purpose of 3D printing this marker plate so that it fitted exactly onto the tibia and allowed the influence of soft tissue oscillations to be minimised in the motion tracking of the shank segment (Furlong et al., 2020). In turn, this permitted higher frequency signal components of the lower limb to be retained in the movement data.

All participants performed a static trial for establishing the joint centre from markers, then 10 trials of fast running at an average speed 6.26 ± 0.24 ms^{-1} for males and 5.71 ± 0.3 ms^{-1} for the female, 45°cutting with an approach speed 5.83 ± 0.2 ms^{-1} for male and 5.41 ± 0.29 ms^{-1} for female (approach speed: performed with maximal speed) and bilateral drop jumping from a 40 cm height. All participants performed the dynamic movements with their dominant leg landing on a Kistler (1600 Hz, Winterhur, Switzerland) force platform. Motion data were recorded using 10 optoelectronic cameras sampling at 400 Hz (Oqus, Qualisys, Gothenburg, Sweden). Three-dimensional marker locations were re-constructed using the Qualisys Track Manager (QTM). Visual 3D (C-motion, Germantown, MD, USA) was then used to construct a kinematic model to quantify movement characteristics. For dynamic motion trials, dominant leg knee moments were calculated between touch-down and take-off. All marker trajectories and force platform data were filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 15 and 30 Hz, prior to calculating the joint angles and joint moments. Two different cut-off frequencies were used to evaluate the effect of retaining higher frequency signal on knee angle, angular acceleration and GRF.

Figure 1: Anterior view of the 3D printed tibio marker plates used for dynamic movements.

For more accurate BSPs, participants' tibia were measured by using data from a whole-body DEXA scanner (QDR 4500W, Hologic, Inc.) and 3D digital scanner. The radius of gyration for medial-lateral (ML) and anterior-posterior (AP) about the centre of mass (CoM) is measured by 3D digital scanner. Participants' shank were divided by 4cm from lateral epicondyle to inferior aspect lateral malleolus (z) for I_{zz} (Axial) using Genley and Powers (2004) method. Additionally, participants' shank were divided into four segments from the end of lateral side to the end of medial side (x) for I_{xx} (ML) about CoM, and were divided into four segments from the end of anterior side to the end of posterior side (y) for I_{yy} (AP) about the CoM.

Participants' segment mass (SM) were measured by DEXA, and then the moment of inertia about three anatomical axes (I_{xx}, I_{yy} and I_{zz}) were calculated using equations below (1):

$$\begin{aligned} &\text{CoM location} = (\textstyle\sum m_i z_i)/SM \\ &I_{xx} = \textstyle\sum m_i(x^2 + z^2)\ (ML) \\ &I_{yy} = \textstyle\sum m_i(y^2 + z^2)\ (AP) \\ &I_{zz} = \textstyle\sum m_i {z_i}^2\ (Axial) \end{aligned} \tag{1}$$

All procedures were approved by Greater Manchester East Research Ethics Committee and the institutional committee and all participants provided informed consent. These data (default: cadaver based data and customised: DEXA and 3D scan based data) were compared using paired t-tests (SPSS 26, Inc., Chicago, IL).

RESULTS: Customised (DEXA and 3D scan) CoM location about three anatomical axes (ML, AP and Axial) were significantly moved 0.39 cm to the lateral side, 0.09 cm anteriorly and 0.01 cm proximally compared to the default settings in the Visual3D software. There was also a significant difference between default and customised values for the moment of inertia (I_{zz}) (see Table 1).

There was a significant difference between BSP default and BSP customised peak moment data during the fast running task (sagittal and transverse plane). However, the peak values were minimally changed with the flexor moment slightly smaller (-0.02 Nm/BW) than default, and internal rotational moment slightly bigger (0.02 Nm/BW) compared to default (see Table 1).

Table 1: Comparisons between default and customised for segment mass, CoM location, moment of inertia and peak moment values.

	Mean (± Std)		Cohen's d (effect size)	*P*-value
	Default	Customised		
Segment Mass (kg)	3.31 (0.49)	3.31 (0.48)	-0.02	$P = 0.931$
CoM – ML (Cm from lateral end)	0 (0)	0.39 (0.27)	1.44	$P < 0.001$
CoM – AP (Cm from anterior end)	0 (0)	0.09 (0.01)	15.32	$P < 0.001$
CoM – Axial (Cm from proximal end)	0.18 (0.01)	0.17 (0.01)	3.38	$P < 0.001$
Moment of inertia, I_{xx} (kg m^2)	0.05 (0.01)	0.05 (0.01)	-0.35	$P = 0.158$
Moment of inertia, I_{yy} (kg m^2)	0.05 (0.01)	0.05 (0.01)	-0.37	$P = 0.131$
Moment of inertia, I_{zz} (kg m^2)	0.0045 (0.001)	0.0053 (0.0008)	-1.5	$P < 0.001$
Peak moment - Running x (Nm/BW)	2.77 (0.74)	2.79 (0.75)	-0.97	$P < 0.05$
Peak moment - Running z (Nm/BW)	0.48 (0.14)	0.46 (0.13)	0.73	$P < 0.05$

x: flexion/extension and z: internal rotation/external rotation

Ground reaction force (GRF) and angular acceleration data appeared to be excessively smoothed by the 15 Hz cut-off frequency. Customised knee joint moment peak magnitude was slightly smaller than default in sagittal plane, and customised knee joint moment peak magnitude was larger than the default values in the transverse plane (see Table 1 and Figure 2).

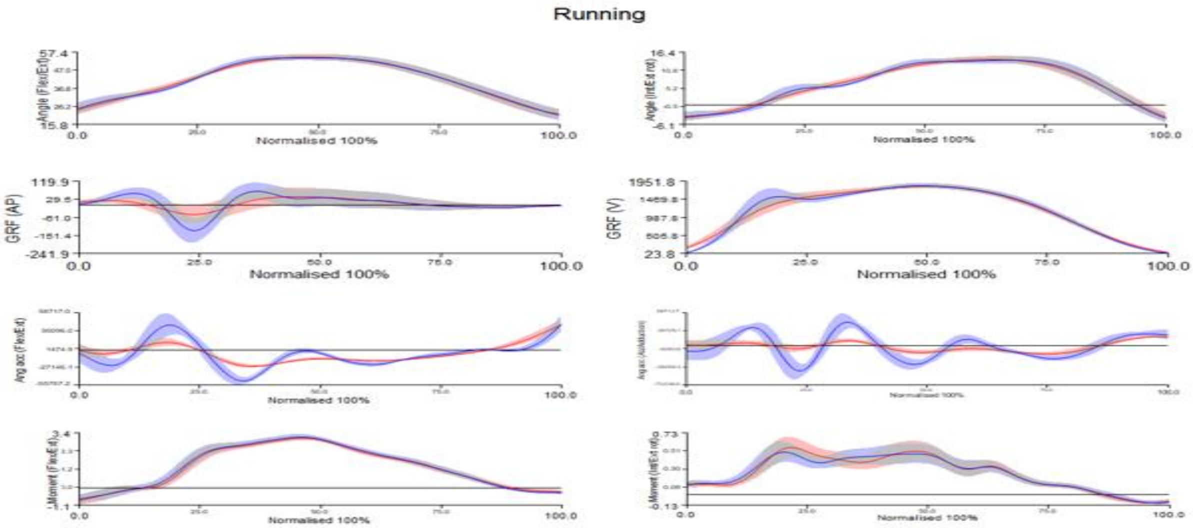

Figure 2: Running graphs of sagittal plane: flexion/extension (column 1) and transverse plane: internal/external rotation (column 2). Angle (°) – row 1, GRF (N) – row 2 and angular acceleration (°/s^2) – row 3 between 15 and 30 Hz cut-off frequency. Moment (Nm/BW) – row 4 between default and customised. (Red – 15 and blue line – 30 Hz cut-off frequency: row 1, 2 and 3. Red – customised and blue line – default: row 4)

DISCUSSION: Customised shank BSPs accounted for the actual shape of each individuals shank instead of using a geometrical shape and ratio data based on information from cadavers (Lee et al., 2009). The customised shank segment had small changes in CoM locations in ML and AP directions compared to default values (which are located in the middle of the truncated cone shape of the shank). CoM location was also moved in the proximal direction axial direction and moment of inertia (I_{zz}) was significantly increased. These results are consistent with a previous investigation of custom versus default BSPs (Lee et al., 2009). Knee angle, knee angular acceleration and GRF were over-smoothed by using a 15 Hz filter cut-off frequency. These results highlight the effect of lower cut-off frequencies, which can smooth and distort kinematic and kinetic data (Tomescu et al., 2018). In terms of peak values with 30 Hz filtering frequency, the effect of BSPs to the knee joint moment peak magnitudes were non-significant between default and customised in cutting 45° and drop jumping. This result is similar to the result of differences between default and customised BSPs from touch-down to take-off, knee joint moments were the least influenced (Muri et al., 2008). Camomilla et al. (2017) reported the effect of BSPs, anatomical landmark definition, marker placement, soft tissue artefact and 0.5 Hz adjustments in the cut-off frequency of the filter used to process the data, on the magnitude of joint moments, She found that BSPs had the smallest influence on joint moment calculations. However, knee joint moment peak magnitudes in running were significantly changed by BSPs in the sagittal and transverse plane. However, these peak values only changed slightly due to corresponding small changes in the custom BSPs. This means is that knee joint moment peak magnitudes are not much affected by the change in BSPs in the current study.

CONCLUSION: The results of this study indicate that the effect of BSPs on knee joint moment peak magnitudes during dynamic movements were minimal. This is related to the fact that, for the current group of subjects, the customised, individual BSPs were similar to values estimated from cadaver-based data (default BSPs). The small BSP differences were not sufficient to influence knee joint moment magnitudes despite high segmental accelerations being maintained in the datasets. However, it remains to be determined whether large individual changes in BSP’s with customised measurements are able to influence the magnitude of peak joint moments during dynamic tasks.

REFERENCES:

Clauser, C.E., McConville, J.P. and Young, J.W. (1969). Weight, volume and center of mass of segments of the human body. Ohio: Aerospace Medical Research Laboratories.

Camomilla, V., Cereatti, A., Cutti, A.G., Fantozzi, S., Stagni, R. and Vannozzi, G. (2017). Methodological factors affecting joint moments estimation in clinical gait analysis: a systematic review. *Biomedical Engineering Online*, 16:106.

Dempster, W.T. (1955). Space requirement of the seated operator. Ohio: Aerospace Medical Research Laboratories.

David, S., Komnik, I., Peters, M., Funken, J. and Potthast, W. (2017). Identification and risk estimation of movement strategies during cutting maneuvers. *Journal of Science and Medicine in Sport*, 20(12), 1075-1080.

Furlong, L.M., Voukelatos, D., Kong, P.W. and Pain, M.T.G. (2020). Changes in inertial parameters of the lower limbs during the impact phase of dynamic tasks. *Journal of Biomechanics*, 99(23), 109488.

Ganley, K.J. and Powers, C.M. (2004). Determination of lower extremity anthropometric parameters using dual energy X-ray absorptiometry: the influence on net joint moments during gait. *Clinical Biomechanics*, 19(1), 50-56.

Hanavan, E.P. (1964). A mathematical model for the human body. Technical Report AMRL-TR-64-102, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, OH, 64-102.

Kim, C.M. and Eng, J.J. (2004). Magnitude and pattern of 3D kinematic and kinetic gait profiles in persons with stroke: relationship to walking speed. *Gait and Posture*, 20(2), 140-146.

Lee, M.K., Le, N.S., Fang, A.C. and Koh, M.T.H. (2009). Measure of body segment parameters using dual energy X-ray absorptiometry and three-dimensional geometry: an application in gait analysis. *Journal of Biomechanics*, 42(3), 217-222.

Muri, J., Winter, S.L. and Challis, J.H. (2008). Changes in segmental inertial properties with age. *Journal of Biomechanics*, 41(8), 1809-1812

Robinson, M.A. and Vanrenterghem, J. (2012). An evaluation of anatomical and functional knee axis definition in the context of side-cutting. *Journal of Biomechanics*, 45(11), 1941-1946.

Tomescu, S.S., Bakker, R., Beach, T.A.C. and Chandrashekar, N. (2018). The effect of filter cutoff frequency on musculoskeletal simulations of high-impact movements. *Journal of Applied Biomechanics*, 34(4), 336-341.

Vanrenterghem, J., Gormley, D., Robinson, M. and Lees, A. (2010). Solutions for representing the whole body centre of mass in side cutting manoeuvres based on data that is typically available for lower limb kinematics. *Gait and Posture*, 31(4), 517-521.