# THE SENSITIVITY OF JOINT KINEMATICS AND KINETICS TO MARKER PLACEMENT ERROR DURING A CHANGE OF DIRECTION TASK

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The conventional gait model has been used in the analysis of change of direction tasks to identify biomechanical risk factors for anterior cruciate ligament (ACL) injury. Several kinematic and kinetic variables have been associated with increased ACL loading during change of direction. Kinematic and kinetic variable calculations are affected by marker placement. The aim of this study was to determine the sensitivity of joint kinematics and kinetics to marker placement error during a change of direction task. Displacements were applied to the lateral thigh, lateral femoral epicondyle and lateral tibia markers. Statistical parametric mapping was used to examine the effect of these displacements across stance phase. Errors in marker placement within the reported inter-tester variability resulted in significant differences in several kinematic and kinetic variables across large periods of stance phase.

**KEYWORDS:** marker placement, change of direction, anterior cruciate ligament.

**Introduction:** The conventional gait model was initially developed for gait analysis in clinical populations, but its use has since been extended to a variety of sporting movements (Hewett et al., 2005, King et al., 2018). Common amongst these is the running change of direction. Change of direction is the most common mechanism of non-contact anterior cruciate ligament (ACL) injury (Geli-Alentorn et al., 2009). Following primary ACL injury, individuals are at high risk of subsequent injury to both the ipsi and contralateral ACLs (King et al., 2018). The conventional gait model has been utilised in the analysis of change of direction tasks to identify biomechanical risk factors for primary and secondary ACL injury (King et al., 2018). Several kinematic variables have been associated with increased frontal plane knee loading during change of direction, considered a key mechanism on non-contact ACL injury (Havens & Sigward, 2015; Kristianslund et al., 2014). These findings have informed clinical practice in ACL rehabilitation and prevention programs.

In order to make clinical recommendations related to ACL injury based on data collected across different laboratories and by different practitioners, we must initially establish the sensitivity of joint kinematics and kinetics to systematic marker placement error. The conventional gait model uses the position of skin-mounted retroreflective markers to define segment origins and orientations. Variation in marker placement is cited as the primary factor in the low reliability indices reported for many kinematic and kinetic variables (McGinley et al., 2009). Inter-tester variability in marker placement has been reported to range between 12 – 25 mm (Della- Croce et al., 2005). Errors in the anterior/posterior positions of the lateral thigh (THI), lateral femoral epicondyle (KNEE) and lateral tibia (TIB) markers will affect joint kinematics and kinetics at the hip, knee and ankle (Groen et al., 2012). The aim of this study was to determine the sensitivity of joint kinematics and kinetics to displacements in the anterior/posterior positions of the THI, KNEE and TIB markers during the stance phase of a change of direction task.

**Methods:** Fifty participants took part in this study. All participants were male, aged 18-35 (mean ± SD: 24.8 ± 4.8, height 180 cm ± 6 and mass 84 kg ± 15.2) and had undergone anterior cruciate ligament reconstruction (ACLR) approximately 9 months previously (8.7± 0.7). Participants completed three trials of a 90° maximum-effort change of direction task on their operated and non-operated limbs. The task involved a 5 m sprint followed by a 90° cut

off their contralateral limb, i.e. plant their left foot on the force plate to turn right, followed by a 2 m sprint to the finish line (King et al. 2018). A synchronised 10-camera optical motion capture (200Hz; Bonita B10, Vicon Motion Systems Ltd, Oxon, UK) and force plate (1000Hz; AMTI, MA, USA) system was used to record ground reaction forces and the positions of reflective markers placed on the body during the manoeuvre. Markers were placed in accordance with the Plug-in-Gait (PiG) marker set, Vicon's implementation of the conventional gait model (Nexus 2.7, Vicon Motion Systems Ltd, UK). Prior to testing, all participants completed a standardised warm-up routine involving jogging, squats and jumps. Data from the operated limb were used for further analysis.

Systematic displacements were applied to the THI, KNEE and TIB markers in software (MATLAB, The MathWorks Inc., MA, USA). Displacements were applied about the corresponding segment co-ordinate system $x$-axis, in 5 mm increments from 25 mm posterior to 25 mm anterior. This resulted in the creation of three separate data sets (A, B and C). Dataset A contained THI marker displacements, B contained KNEE marker displacements and C contained TIB marker displacements. Tri-planar angles at the hip, knee and ankle as well as knee joint moments were extracted during stance phase, identified by start and end of the ground reaction force (>20N). Kinematic and kinetic waveforms were time normalised to 101 data points. Motion and force data were low-pass filtered using a fourth order bidirectional Butterworth filter (15Hz) (Kristianslund, Krosshaug, & Bogert, 2012). The mean of each subject's three trials was used for further analysis.

We subsequently conducted a sensitivity analysis using one-dimensional parametric mapping (SPM) (Pataky et al., 2013). For clarity, we will use the example of one dataset, dataset A, as the process was repeated identically for datasets B and C. Each variable from dataset A was submitted to a 1D independent samples SPM t-test between the original unaltered marker position data and each of the marker displacement conditions. This resulted in the creation of 10 SPM {t} curves for each variable, one for each marker displacement. The significance of each SPM {t} curve was determined topologically using random field theory (α=0.05; Pataky et al., 2013). Phases of the SPM {t} curve which were above the corresponding critical-$t$ threshold were deemed to be significantly affected by marker displacements.

**Results:** Results for each sensitivity analysis are presented in Figure 1. Hip rotation and knee abduction angles were the most sensitive variables to THI marker displacement. 10 mm anterior/posterior displacements caused significant differences in these variables across the entire stance phase (Fig 1A). Knee rotation angle, ankle abduction and rotation angles as well as knee flexor moment were also significantly affected for periods of stance phase by THI marker displacements.

Ankle rotation angle was the most sensitive variable to KNEE marker displacement. 10 mm anterior/posterior displacements caused significant differences during the first 20% and last 20% of stance. As displacements increased further, a larger percentage of the waveform was affected. At 25 mm anterior/posterior displacement, the entire stance phase was significantly affected (Fig 1B). Hip rotation, knee flexion, abduction and rotation, knee flexor moment and knee abduction moment were also significantly affected by KNEE marker displacements (Fig 1B).

Knee rotation angle was the most sensitive variable to TIB marker placement, and the only variable in any condition to be significantly affected by 5 mm anterior/posterior displacements across the entire stance phase (Fig 1C). 10 mm anterior/posterior displacements caused significant differences in ankle abduction and rotation angles across

the entire stance phase. Ankle plantar flexion, knee flexor moment and knee abduction moment were also significantly affected by TIB marker displacements (Fig 1C).
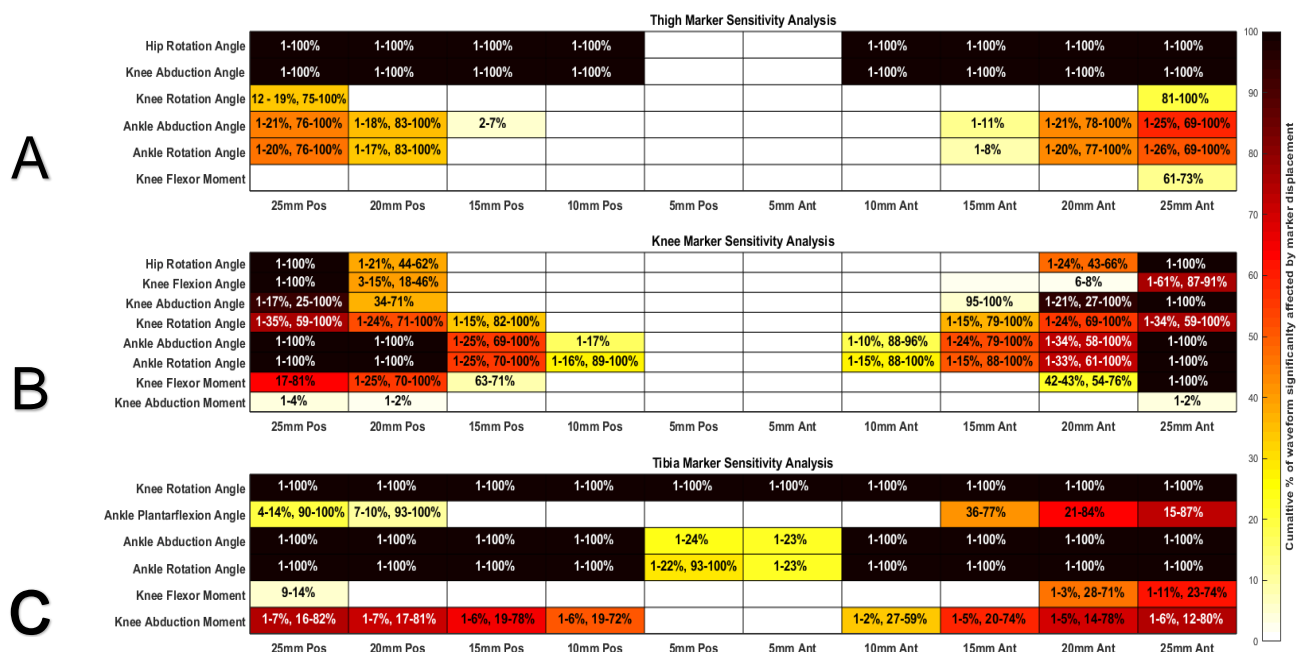


Fig. 1. Sensitivity analyses for THI **(A),** KNEE **(B)** TIB **(C)** markers. In-bar text corresponds to the specific phases of the waveform significantly affected by the corresponding marker displacement. Colour corresponds to the cumulative percentage of the waveform significantly affected by the corresponding marker displacement. Only variables significantly affected by marker displacements are shown.

**Discussion:** Our findings indicate that systematic differences in marker placement can significantly affect multiple kinematic and kinetic variables during the stance phase of a change of direction task. Several variables were significantly affected by marker displacements within the previously-published inter-tester variability for the associated anatomical landmarks (Della-Croce et al, 2005). These include hip and ankle rotation angles as well as knee abduction moment. Increased hip internal rotation and ankle external rotation at initial contact have previously been associated with frontal plane knee loading during change of direction (Kristianslund et al., 2007; Dempsey et al., 2007). Our data indicate that these discrete measures would be significantly affected by systematic differences in marker placement (Fig 1).

The most sensitive variable in our analysis was knee rotation angle under tibia marker displacements, with 5 mm anterior/posterior displacements causing significant errors across the entire stance phase. The anterior/posterior position of the TIB marker determines the orientation of the ankle/flexion extension axis. Anterior placement internally rotates the axis, while also moving the estimated ankle joint centre (AJC) posteriorly. This affects the anterior/posterior angulation of the shank and femur segments, resulting in the large observed errors in knee rotation angle (Groen et al., 2012).

Marker displacement in a particular direction has a unidirectional effect on the reported outcome variables, meaning that a true population difference exists and the distribution of differences does not overlap zero. The test statistic is therefore a function of effect size and sample size. At smaller sample sizes, marker displacements required to reach significance levels would be larger. The exact displacement thresholds required to reach significance are limited to our chosen sample size. However, our findings do indicate which variables are most sensitive to marker displacements as well as which marker has the largest effect on each variable.

**Conclusions:** Systematic differences in marker placement can significantly affect biomechanical variables related to ACL injury. Our results indicate the minimum systematic differences in the placement of the THI, KNEE and TIB markers required to cause significant differences in these variables at a sample size of n = 50. These thresholds can be used by laboratories as guidelines for acceptable levels of inter-tester variability in marker placement. If inter-tester variability is above these thresholds, these variables should not be reported on. Previously published ranges of inter-tester variability in marker placement can also be combined with our findings to aid in the interpretation data published from multiple laboratories.

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