THE EFFECTS OF CONSTRAINING OPENSIM INVERSE KINEMATICS TO A BONE PIN MARKER DEFINED RANGE

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The aim of this study was to apply bone pin kinematic constraints to an OpenSim model to determine differences in knee joint kinematics and kinetics between the constrained and unconstrained solutions. In vivo data from healthy, anterior cruciate ligament deficient and reconstructed patients completing a forward jump lunge were combined with bone pin data from a past study to redefine ranges that the knee degrees of freedom were constrained to. Differences between the constrained and unconstrained solutions existed for all participants at various points of the jump lunge movement, especially at the time of impact. Soft tissue artifact was most apparent in transverse plane translations. In conclusion, musculoskeletal modelling based solely on surface marker positions is inherently affected by soft tissue artifact and thus, results from these analyses should be interpreted with caution.

KEY WORDS: Soft tissue artifact

INTRODUCTION: Human movements can easily be recorded and analyzed through modern motion capture systems and with the addition of electromyography, researchers can draw correlations between muscle activations and movement patterns. Unfortunately, with this type of in vivo research, the cause-and-effect relationship between the movement and neuromuscular system remains undefined and thus, making alterations and improvements quite difficult. To address this issue, computer simulations of human movement have garnered increasing attention from researchers and a widely available, open-source software package called OpenSim (Delp et al., 2007) has come to the forefront of the biomechanics research field. OpenSim allows researchers to directly measure the effect that altered muscle forces have on human movement, which can ultimately define this previously indeterminate cause-and-effect relationship.

Since this advanced software is dependent on inputs collected through motion capture systems, it too is greatly affected by measurement sources of error including soft tissue artifact (Leardini et al, 2004). In an effort to quantify the amount of soft tissue artifact during gait and cutting motions, Benoit et al. (2006) outfitted participants with both skin markers and markers attached to bone pins, which were inserted into the proximal tibia and distal femur. Average rotational errors in the side cut were 13.1° while translational errors reached 16.1 mm. If musculoskeletal modelling is to accurately predict muscle forces, the kinematics must be properly represented. With the current practice of arbitrarily defining a range for joint degrees of freedom (dof), we introduce errors into the modelled movement and thus, make any computations from these data suspect. Therefore, the purpose of this study was to apply bone pin kinematic constraints to an OpenSim model to determine the difference in knee joint kinematics and kinetics between the constrained and unconstrained solutions. It was hypothesized that the soft tissue artifact during ballistic movements will be reduced as evidenced by the removal of non-physiological knee joint translations and rotations once the bone pin derived constraints have been implemented.

METHODS: A total of 42 participants were included in this study. Of these, 12 were healthy males (A:27.3 ± 6.8 y, H:1.81 ± 0.06 m, W: 80.6 ± 11.0 kg), 12 healthy females (A:24.5 ± 5.9 y, H:1.70 ± 0.05 m, W: 62.0 ± 8.1 kg), 12 males pre (A:28.9 ± 6.0 y, H:1.81 ± 0.05 m, W: 82.5 ± 7.9 kg) and 10.2 ± 1.5 months post ACL reconstruction (ACLr; A:29.2 ± 5.1 y, H:1.80 ± 0.05 m, W: 81.9 ± 9.2 kg), and 6 females pre (A:24.0 ± 6.0 y, H:1.67 ± 0.07 m, W: 57.0 ± 12.9 kg), and 10.0 ± 2.0 months post ACLr (A:25.9 ± 5.9 y, H:1.67 ± 0.08 m, W: 64.2 ± 10.7 kg). The injured limb was tested for the ACL group while the dominant leg was tested for the healthy participants. Participants were outfitted with a hybrid plug-in-gait/cluster marker set. Kinematic data were collected using a 10-camera motion capture system (6 MX and 4 T series, Vicon, UK) and captured at 100 Hz. Kinetic data were sampled at 1000 Hz using three force plates (OR 6-5-1, AMTI, USA). Participants completed 3-5 successful jump lunges where they were asked to stand on their non-injured or non-dominant leg and jump forward with their test or dominant limb onto a force plate and maintain balance for two seconds. Jump speed and length were not normalized but to avoid stepping, participants were encouraged to select a comfortable speed and distance to ensure it was a forward jump. Jump lunges were cropped 100 ms pre contact to 300 ms post contact.

All data were processed through a Matlab (2013a, Mathworks, USA) - OpenSim (3.3, Simtk, USA) application program interface. Both kinematics and kinetics were filtered using a 4th order zero-lag low pass Butterworth filter with matching cut-off frequencies of 15 Hz. The Gait4392 model (Hamner et al. 2010) was adapted to reduce the number of lower limb muscles to 46 and include patellae and six dof at the knee. Data were scaled and processed through inverse kinematics (IK) and inverse dynamics (ID) to achieve the no bone pin constrained (NoBP) results. Bone pin data from Benoit et al. (2006) were collected for 3 to 5 motion capture trials of each walking, hopping and cutting motions from 6 healthy young adult males as described in their published work. These data were processed to create boundary envelopes of each dof as a function of knee flexion angle to be used as the full ranges of motion for each of the knee model's 5 other dofs. For all trials in each individual, a mean and 95% confidence interval (CI) for each dof were taken and these 95% CIs were then averaged to determine the range that the knee joint was constrained to for each dof. Therefore, every sagittal plane knee angle is associated with its range that constrains the movement of the remaining five dofs. The same scaled models were then subjected to IK once again where the calculations were completed at each time point (every 0.01s) and the knee dofs were adjusted so that their kinematics were constrained to the range defined by the 95% CI of bone pin trials and associated with the current knee flexion angle at that instant in time. These new kinematic results were then used to calculate ID (BP).

Differences in the knee joint kinematic and kinetic waveforms were tested for through statistical parametric mapping (SPM). Paired sample T-tests were used to test the two conditions of bone pin constraints and surface marker results. Alpha was set to a significance level of 0.05.

RESULTS: When bone pin constraints were used to calculate IK, the knee joint had a significantly larger flexion (1-4°), adduction (3-5°), and internal rotation (1-3°) angle from the point of contact onwards for all groups compared to when only the surface markers were used to track the motion. Additionally, BP IK produced significantly greater posterior tibial placement (2-10°) in relation to the femur and a more distracted knee joint (Figure 1) for the entire movement in all groups. Prior to contact and the immediate 100 ms following contact, the tibia was situated more medially (1-

6°) with respect to the femur for both the healthy males and females while in the male ACLr, the same shift was observed from the point of contact onwards.

In joint kinetics, BP produced significantly greater flexion (0.1-0.2 Nm/kg) and adductor (0.2-0.4 Nm/kg) moments at the point of contact while immediately after contact, the BP constraints produced similar flexor moments, but greater abductor (0.1-0.2Nm/kg) and external rotator moments (0.1Nm/kg). The only change in medial/lateral shear force occurred in the healthy females where BP ID solved for a significantly more lateral shear force (0.7N/kg). From the point of contact onwards, BP ID also solved for a significantly greater anterior tibial shear (0.5-1N/kg) and distractive (1-2N/kg) force in all groups.

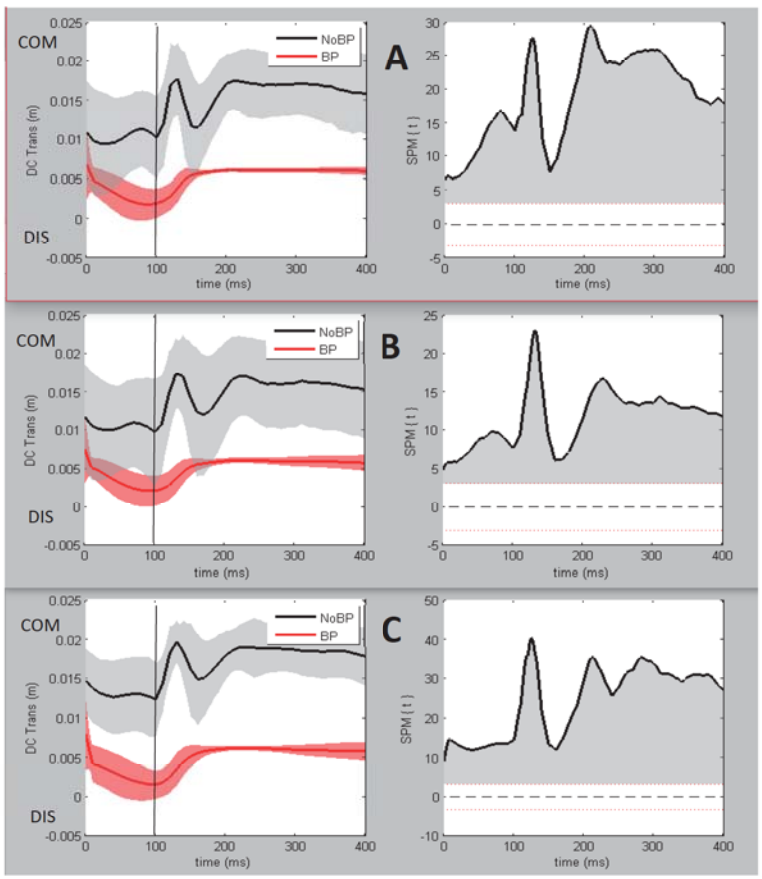

Figure 1. Distraction/Compression translations (m) for healthy controls (A), ACL deficient (B), and ACL reconstructed (C) patients. Vertical line at 100 ms represents contact. Figures on the left are means and standard deviations for no (black) and bone pin (red) kinematic constraints. Figures on the right are SPM results, where grey areas represent significant differences.

DISCUSSION: With the addition of bone pin kinematic constraints to surface marker trajectories, significant differences in kinematics and kinetics were observed for all six degrees of freedom at the knee joint. These differences occurred throughout the entire movement but were most distinct at the point of contact (100 ms). This was also very clear during the animations produced in the OpenSim GUI as the ballistic landing of the leg elicits large amounts of soft tissue artefact. The translation ranges used in Xu's knee model (2015), which is the most biofidelic knee joint model currently available, are six centimetres for anterior /posterior translation and 4 centimetres for medial/lateral and distraction/compression translations. These values are well beyond the physiological ranges and thus result in non-physiological IK solutions, not to mention dislocated knees.

Our results are in agreement with the errors noted by Benoit et al. (2006) as frontal plane angle errors reached up to 6° while transverse angle errors were within 5°. Translation errors reached 8 mm, 7 mm, and 15 mm in the sagittal, frontal, and transverse planes respectively. It is expected that these errors would increase as the motion involves more movement in the frontal and sagittal planes, as what was described in Benoit et al. (2006) when side cuts elicited larger discrepancies between bone pin and surface markers. The non-physiological soft tissue artifact was most apparent in transverse plane kinematics as seen in Figure 1. The no BP solutions allowed for large spikes shortly after impact, which is due to the inertia experienced by the skin markers. When BP constraints were applied, this soft tissue artifact was removed.

These results also have clinical relevance to ACL injuries as the mechanisms of non-contact ACL injuries have been recognised to be a combination of an anterior shear force, knee abduction and internal rotation moments (McLean, 2003). Our results show that differences in joint moments and shear forces occur when soft tissue artifact is accounted for. Therefore, the lack of group differences in many studies could be due to a false negative being caused by soft tissue artifact affecting the ID calculations.

CONCLUSION: Caution should be expressed when using the results from musculoskeletal modelling as soft tissue artifact can introduce error in both the kinematics and kinetic calculations. This error is amplified during ballistic and high impact tasks such as jump landing.

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