DETERMINING INITIAL KNEE JOINT LOADING DURING A SINGLE LIMB DROP LANDING: REDUCING SOFT TISSUE ERRORS

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This study examined the influence of modeling approaches on lower limb on transient knee joint moments during single leg landings. A typical 6DoF joint model was compared to a constrained 3DoF model. For peak moments and rates of moment increases there was no difference between joint models. Earlier, and greater moments were obtained using data from a 3D-printed plate moulded to each individual's tibia. Maintaining high frequencies in the dataset using the 3D-printed plate was important for determining initial joint loading and associated risk factors for sports injuries.
Key words: 6DoF, 3DoF, Knee, Inverse Kinematics, Modeling, Signal Frequencies.

INTRODUCTION: Ground reaction forces (GRF's) and movement profiles during tasks such as landing from a jump have been used to screen for the risk of sports joint injury (e.g. knee ligament damage (Shultz et al., 2012)). GRF's are assumed to be reasonably accurate but it is generally accepted that the accelerations obtained from kinematic data can be prone to large error (e.g. Bisseling and Hof (2006)). Segment tracking markers have typically been digitally filtered at around 15Hz or less to reduce the influence of soft tissue errors (motion of soft tissue relative to underlying bone, including vibrations) just after landing. To determine joint kinetics, the GRF data is filtered using the same cut-off frequency (e.g. Kristianslund et al. (2013)). However, there are problems with this approach. GRF data can be distorted due to filtering with a low cut-off frequency and joint moments are determined using GRF that does not resemble the GRF that was measured e.g. Roewer et al. (2012). Also, it has been demonstrated that during dynamic activities like running and landing, the movement of the tibia can have significant signal power between 15 and 35 Hz (e.g. LaFortune (1991)).

3D-printed tibial plates that exactly fit onto the skin overlying the surface of each subjects' tibia permit higher frequency movement signals to be maintained in the dataset without increasing soft tissue errors. These higher frequency aspects of shank segment motion are typically filtered out because they overlap with the soft tissue vibration frequencies of the triceps surae (calf) muscle group on which shank marker clusters are often mounted (e.g. Boyer and Nigg (2004)). Another alternative approach to reduce the influence of soft tissue errors in the joint kinetic calculations during dynamic activities is the use of global optimisation (known as inverse kinematics (IK)) to constrain the joints. Typically, a 3 degrees of freedom (DoF) modeling approaches of knee joint motion are employed with just the rotations about the joint permitted and all joint translations constrained (Robinson et al., 2014).

The aim of this study was to compared knee joint moments determined using 3DoF IK to those obtained using the 6DoF approaches (unconstrained) in both defined using a standard calf plate and a custom made 3D printed tibial plate. It was hypothesised that the initial knee joint loading derived from the 6DoF tibial plate approach would be higher than that obtained using the 6DoF calf plate because the influence of soft tissue movement errors would distort the joint kinetic calculations. In addition, it was also hypothesised that the tibial plate would display higher magnitude initial knee joint loading than the 3DoF IK modeling approach. All three peak knee moments were determined as the initial magnitude of non-sagittal plane moments during landing tasks have been associated with the risk of knee ligament injury during court sports (Sigward and Powers, 2006).

METHODS: Sixteen young male and female subjects (mean age, height and mass of 24.6 ± 2.4 years, 1.76 ± 0.09 m and 68.6 ± 9.5 kg, respectively) performed a series of ten controlled, single leg drop (40 cm) landings onto a force platform (Kistler, Switzerland).
For the kinematic analysis of each landing, slightly curved marker plates (each with four reflective markers) were tightly mounted on the lateral calf and thigh of the right leg (mass 34 and 36 grams, respectively) using both an underwrap and overwrap of stretch bandage. Four tracking markers were also placed on the shod foot (heel and forefoot) to track movements of the foot. Segment-defining markers were positioned at the maleolli of the ankle, medial and lateral knee joint axes and the greater trochanter of the hip joint. Participants had the lower third of the anterio-medial surface of their right tibia scanned using a 3D scanner. The scan was converted into a solid before being transferred into Solidworks CAE package (Solidworks, Solid Solutions, Leamington Spa, U.K) where a 5cm wand and marker platform was added. The plate was then printed from a 2004 Dimension Elite (Stratasys, Minnesota, USA) on ABS Plastic. This lighter, rigid plate (mean mass = 17.4 +-2.4 g) was tightly fitted on the skin over the anterio-medial lower third of the tibia with non-stretch tape. This tibial plate had three reflective markers (one on the wand and two on the plate surface).

Kinematics were sampled at 500 Hz using a six-camera opto-electronic system (Oqus 300, Qualisys, Sweden). In order to mimic data processing approaches commonly used the literature, kinematic data were filtered using a Butterworth dual pass digital filter with a cut-off frequency of 15 Hz. The GRF data was filtered using the same cut-off before knee joint moments were calculated using Visual3D software (C-Motion, Canada) with the calf plate used for shank segment tracking (Kristianslund et al., 2013). For both data processing approaches, the peak knee moments (in all three knee rotations) during the first 50ms were determined. Also in that phase, the peak instantaneous rate of moment development (ILR) was determined (after differentiating the moment curves). This loading rate variable has been associated with the risk of injury (e.g. (Kipp et al., 2011)). Finally, the timing of the ILR from the instant of initial ground contact was calculated. The IK approach (described above) was used on the typical kinematic data filtered at 15Hz and with the shank segment tracked using the calf plate. A 3DoF knee joint constraint (no translations or sliding) was implemented within the Visual3D software using default settings for the Quasi-Newton optimization routine method. One-way ANOVA's were used to determine the influence of marker plate mounting (tibial versus soft-tissue) and optimization using joint constraints on the rate of knee moment development and the peak knee moments during early ground contact of landing ($p<0.05$).

RESULTS: All the initial peak knee moments were significantly larger when determined using the higher frequency tibial plate data compared to the more typical, lower frequency calf plate data (see figure 1A). Peak extensor and internal rotation moments were also larger than those associated with IK optimization. There were no significant differences between the 6DoF and the 3DoF approach in the peak moments generated. ILR was also no different when measured using 6D.oF kinematics or 3D.o.F optimised data. However, figure 1B illustrates that both these ILR were substantially less than the same measures obtained using the tibial plate-derived knee moments. Group mean knee joint moment curves clearly illustrate the earlier initial peaks obtained using the tibial plate data (e.g. see figure 2). The timing of the increase in joint moment is also significantly earlier for the tibial plate data (see figure 3).

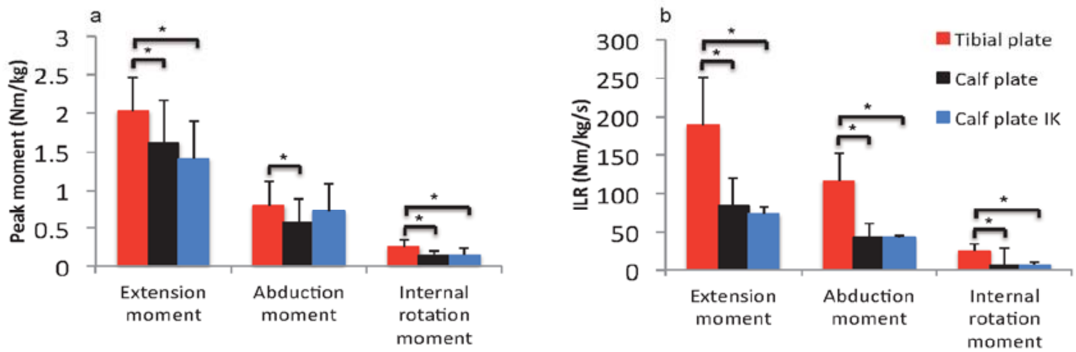

Figure 1. Peak knee moments (a) and instantaneous rates of moment development (b) during landing for the three modeling approaches. Notice that peak moments and rates of moment development are generally higher when determined using the higher frequency tibial plate data.

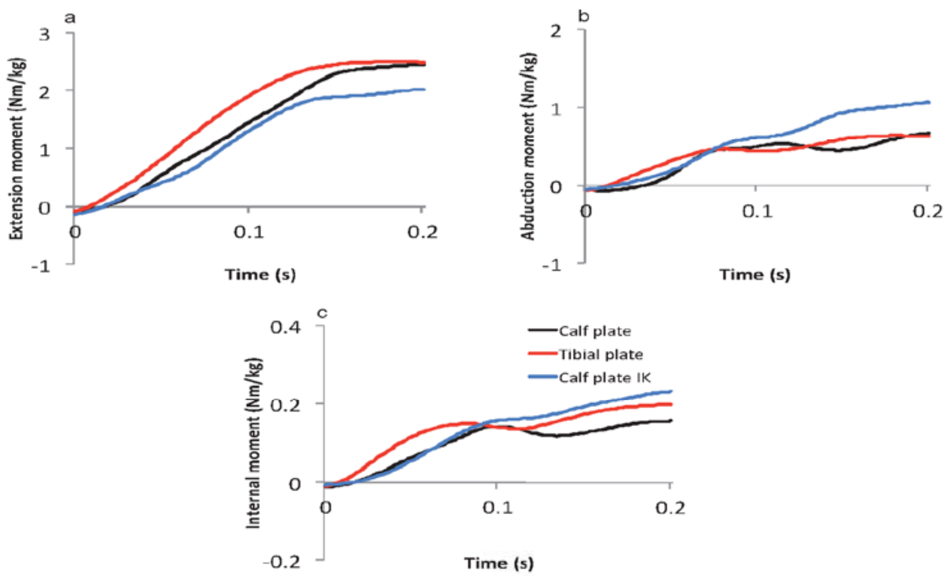

Figure 2. Group mean curves for extension knee moment (a), abduction knee moment (b) and internal rotation knee joint moment (c) during the first 200 ms of landing in the three data analysis approaches.

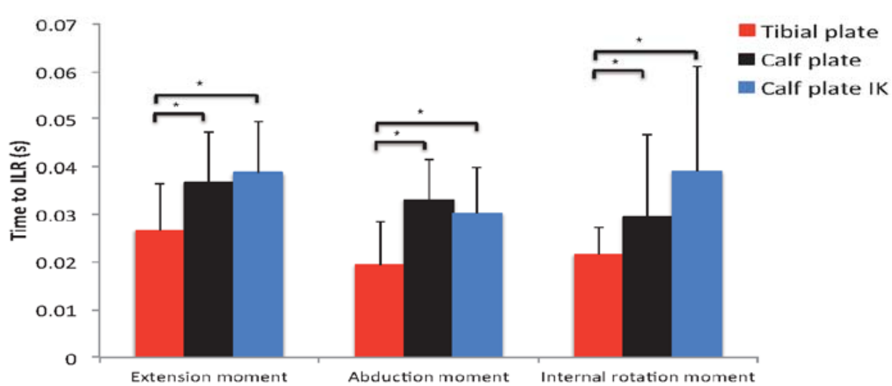

Figure 3. Time of peak ILR from the instant of landing (first 50 ms). Moments derived from the tibial plate data have significantly earlier peak slope of moment.

For the initial range of knee flexion (similar to angles at ground contact during drop landing) there appears to be predominantly rolling of the joint and then later, with more knee flexion and a fully loaded joint, there is more sliding motion which reduces the joint loading (Nagerl et al., 2009). Therefore, its plausible that, if the joint is mainly rotating during early loading, the differences between 3DoF modeling (pure rotation) and 6DoF might be minimal. The greater knee joint moments during early loading measured using the tibial plate data are most likely related to the higher frequency components in kinematic data. These higher frequency signals derived from the tibial plate being are considered to be more reliable and accurate joint moment experienced at the knee compared joint moment derived from a calf plate, that is mounted on a large mass of oscillating soft tissue. While, it is difficult to confirm non-invasively that the higher frequency movements measured are real movements of the tibia, it is acknowledged that the true higher frequency signal of raw GRF data in the present study were severely distorted by filtering at the same cutoff frequency as the motion data (15 Hz) (recommended by Kristianslund et al. (2013)). Therefore, future directions of this study will be to explore the influence of different low-pass cutoff frequencies on knee joint moment data. The benefit of using the tibial plate modeling approach over the calf plate is that it allows a greater potential to use a higher low-pass cut-offs so that the true higher frequency signals associated with initial impact loading are contained within the dataset rather them being typically discarded using a calf mounted plates.

CONCLUSIONS: Attempting to reduce soft tissue errors through optimisation of knee motion using joint translation constraints, did not appear to modify the magnitude and timing of initial knee joint moments during a single leg drop landing. In contrast, joint moments derived from kinematic data obtained from a customised tibial plate displayed substantially higher initial joint loading. This greater joint loading may be related to real, higher frequency signals being maintained in the knee moment data rather than typically discarded.

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