OPTIMIZING WHOLE BODY KINEMATICS TO REDUCE PEAK NON-SAGITTAL PLANE KNEE LOADS DURING SINGLE LEG JUMP LANDING TASK TO REDUCE RISK OF ACL INJURY

[1]Dhruv Gupta, [2]Jeffrey A. Reinbolt, [1]Jody L. Jensen and [3]Cyril J. Donnelly

[1] University of Texas at Austin, Austin, TX, USA
[2] University of Tennessee, Knoxville, TN, USA
[3] The University of Western Australia, Perth, Western Australia, Australia
email: dhruv.gupta@utexas.edu

INTRODUCTION

In the United States, every year over 200,000 anterior cruciate ligament (ACL) injuries occur [1, 2]. Approximately 60% of these are non-contact in nature, with >90% occurring during single-leg jump landing (SLJL) or sidestepping [3, 4]. Anterior tibial force in conjunction with non-sagittal plane (valgus, varus and internal rotation) knee moments has been shown to place the maximum strain on the ACL [5]. During landing and sidestepping the peak loads are typically observed during the weight acceptance or the impact phase of the movement [6].

Using the residual reduction algorithm (RRA) tool in OpenSim musculoskeletal modeling framework, optimized kinematics that reduce peak valgus knee moments can be solved for [7]. They used outer level optimization tool [8] which makes the simulations work with negligible residual forces not allowing the reduced knee loads to simply shift to the residual forces.

As acknowledged by Donnelly et al. (2012) [7], one of the primary limitations of their simulation work was the absence of a foot-contact model that would prevent inappropriate translations of the foot like breaking the plane of the floor. Use of zero-moment point (ZMP) computations [9] to give a dynamically consistent ground reaction force (GRF) for each simulation is a promising solution to this problem. A secondary limitation of this study [7] is that only peak valgus knee moment was reduced and not all the non-sagittal plane knee moments.

The purpose of this study is to a) integrate the ZMP computations [9] within outer level optimization tool [8] to produce simulations of SLJL task during weight acceptance phase, with dynamically consistent GRF using the RRA tool in OpenSim and b) using these simulations, find the optimal whole body kinematic pattern that reduces the non-sagittal plane knee moments to reduce ACL injury risk.

METHODS

Step 1: Producing simulations: Methods used by Donnelly et al (2012) [7] create joint torque driven simulations with negligible model residuals were integrated to ZMP computations [9]. This creates simulations with negligible residual forces and with dynamically consistent GRF (fig. 1). The cost function $J(x)$ of the outer level optimization tool was modified to not only reduce the errors in model kinematics, residuals and torque excitations, but also the foot translation errors, GRF errors and COP errors.

$$J(x) = \min_{x^R,x^T}[\sum_{i=1}^{n_q} w_{\ddot{q}_i}\left(\ddot{q}_i^{exp.} - \ddot{q}_i^{sim.}\right)^2 + \sum_{j=1}^{6} w_R\left(\frac{R_j\left(x_j^R\right)}{R_j^{max}}\right)^2 + \sum_{k=1}^{n_T}\left(\frac{T_k\left(x_k^T\right)}{T_k^{max}}\right)^2 + \sum_{m=1}^{n_m} w_m(p_m^{exp.} - p_m^{sim.})^2 + \sum_{f=1}^{4} w_f\left(GRF_f^{exp.} - GRF_f^{ZMP}\right)^2 + \sum_{c=1}^{2} w_c(COP_c^{exp.} - COP_c^{ZMP})^2]$$

Where, x^R and x^T are the excitation values for six residuals (R_j) and joint torques (T_k), $p_m$is the position of markers tracked on the foot and q_i are the model kinematics.

Step 2: Reducing non-sagittal knee moments: The maximum allowable joint torques of knee V/V and knee I/E rot were simultaneously reduced until the model crashes, but still producing reasonable simulations with consistent ground reaction forces. Our a priori definition of a reasonable simulation that it has negligible residuals, GRF errors < 10 N, GRF moment errors < 10 Nm and COP errors < 3 cm and foot translation errors < 3 cm compared to the simulations from the first step. This simulation gives us the optimal kinematics that reduced peak non-sagittal plane knee moments for the SLJL task.

Figure 1: Reasonable simulation of SLJL task with dynamically consistent GRF.

We define non-sagittal plane knee moment as vector sum of knee V/V and I/E rot knee moments. Its peak value before and after step 2 was compared. Texas Advanced Computing Center at The University of Texas at Austin was used for all computations.

RESULTS AND DISCUSSION

Five simulations with negligible residuals and consistent GRF for the SLJL task during the weight acceptance phase were produced. All simulations landed on right leg. The peak non-sagittal plane knee moment was reduced by an average of 30.18 ± 18.52 % (29.92 ± 15.16 Nm). Fig. 2 shows the changes in peak knee moments in all three axes individually and the non-sagittal plane knee moment. All but one simulation reduced the peak non-sagittal plane knee moment. The peak knee flexion/ extension moment remained approximately the same except for the first simulation, where the peak knee flexion moment increased. This however, does not increase the risk of ACL injury as it is the non-sagittal plane knee moments that put heavy strain on ACL [5].

For our SJLJ simulations, the change in kinematics after the reduction of the non-sagittal plane knee moments were surprisingly small (a maximum of 1.46 degrees for left hip rotation in simulation 5). 11 out of the 22 significant kinematic differences observed were in sagittal plane, 3 in frontal plane and 8 in transverse plane. Sagittal plane displayed the most kinematic changes in previous side-stepping research as well [7]. Lack of big kinematic changes could be due to the additional tracking of the foot translation and the ZMP computations. This calls for a deeper study of load distribution with more data.

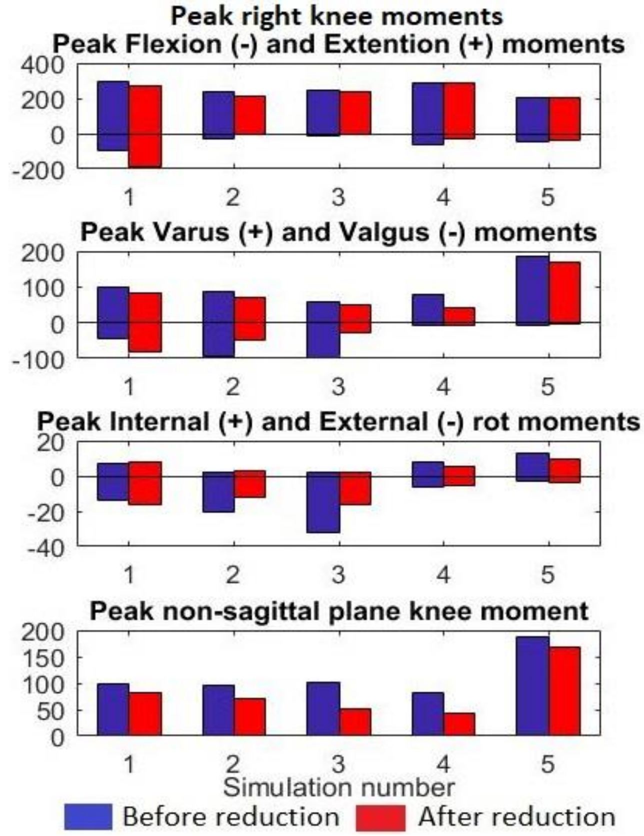

Figure 2: Peak right (landing) knee moments before and after optimizing whole body kinematics to reduce peak non-sagittal plane knee moments.

CONCLUSIONS

This is first time that simulations with negligible residuals and dynamically consistent GRFs have been produced. Optimizing whole body kinematics to reduce peak knee moments has huge implications in preventive medicine. Further research in load distribution in optimized simulations and muscle contributions is needed.

REFERENCES

1. Arendt E and Dick R. *Am J Sports Med*,1995.
2. DeMorat G. et al. *Am J Sports Med*, 2004.
3. Ekegren CL, et al. *J Orthop Sports Phys Ther*, 2009.
4. Hewett TE, et al. *Am J Sports Med*, 1996.
5. Markolf KL, et al. *J Orthop Research*, 1995.
6. Cerulli G, et al. *Knee Surg, Sport Traumatology, Anthroscopy*, 2003.
7. Donnelly CJ et al. *J Biomechanics*, 2012.
8. Reinbolt JA, et al. *Simulation of human movement*, 2011.
9. Reinbolt JA and Donnelly CJ. *Int Society Biomech*, 2017.