COMPARISON OF INDIVIDUAL MUSCLE CONTRIBUTIONS TO GROUND REACTION FORCES DURING JUMP AND CHANGE OF DIRECTION TESTING AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

Rodrigo B. Mateus[1], Sílvia Cabral[1], Chris Richter[2], Andrew Franklyn-Miller[2], António P. Veloso[1]

CIPER, Faculty of Human Kinetics, University of Lisbon, Cruz Quebrada, Portugal[1]
Sports Surgery Clinic, Dublin, Ireland[2]

The purpose of this study was to identify the main muscle contributions across a battery of different tasks commonly used to evaluate an athlete's readiness to return to sport after anterior cruciate ligament injury (ACL) and following ACL reconstruction. These injuries are mostly related to landing and change of direction movements and, due to its high incidence, efforts must be made to better understand the knee soft tissue mechanisms during these types of tasks. Data from a single athlete were analysed for this study. Scaled generic musculoskeletal models, consisting of 12 segments, 23 degrees of freedom and 92 musculotendon actuators were used in OpenSim. The quadriceps were the main contributors to ground reaction forces along the anterior/posterior direction, and, aided by the soleus and gastrocnemii, counteracted most of the effects applied by gravity along the vertical direction. The main contributors to the ground reaction forces during all the tasks are the same muscles that are intimately related to ACL loading, thus making these tasks useful for injury rehabilitation programs.

KEYWORDS: ACL, Musculoskeletal Modelling, Induced Acceleration Analysis.

INTRODUCTION: Non-contact knee injuries are a common occurrence in the world of professional sports, with anterior cruciate ligament (ACL) injuries being common and some of the ones with a more challenging recovery period (H, Shahrbanian, & Khoshroo, 2018). Following injury, the athletes tend to undergo ACL reconstruction (ACLR) via a surgical procedure (Hughes, Musco, Caine, & Howe, 2020). Albeit, after surgery, there is no common ground on which measures are the most related to a player's readiness to return to sport (King et al., 2018). Biomechanical analyses of landing tasks have been used to study the effectiveness of injury prevention protocols and the impact of rehabilitation after ACL reconstruction (Harper, Cohen, Rhodes, Carling, & Kiely, 2021; Nasseri et al., 2021). Also, the use of biomechanical variables instead of performance variables has been shown to provide more complete knowledge on RTP than other variables studied in previous studies (King et al., 2021). Research also shows that subjects, after ACLR, might present abnormal biomechanics that is closely related to lower muscle strength and alterations in knee kinematics (Badawy et al., 2022). These changes in muscle forces following ACLR are observed not only in muscles that span the knee joint, but also in other muscles spanning the hip and ankle joints (Petersen, Taheri, Forkel, & Zantop, 2014). Previous studies also found that, besides the knee-spanning muscles, also important non-knee spanning muscles (e.g. *soleus)* contribute to ACL loading (Mokhtarzadeh et al., 2013). In addition to this, ACL injury prevention programmes are shown to have a positive effect on the vertical ground reaction forces, albeit correct technique whilst performing several jumping tasks is necessary (Padua & DiStefano, 2009). Therefore, understanding lower extremity muscle contributions to the ground reaction forces may provide insight to improving ACL injury prevention protocols.
The main goal of this work was the comparison of different tasks concerning their muscle contributions to the ground reaction forces. With this work, we aim to characterize the different movements implemented in this experimental design in terms of the potential contribution of such muscles.

METHODS: One subject (188.6 cm and 94.4 kg), who underwent ACLR in the right lower limb, participated in this study and gave his written informed consent before the beginning of the study. Biomechanical data were collected using a ten-camera motion analysis system (200 Hz; Bonita-B10, Vicon, UK), synchronized with two force platforms (1000 Hz BP400600, AMTI, USA) recording the positions of 42 reflective markers. The marker setup included the Plug-in Gait model and the 6 Degrees of Freedom models simultaneously, and a full description of the marker set is given in (Scott, Robinson, & Daniels, 2020). After a warm-up, the participant completed a testing battery consisting of bilateral and unilateral countermovement and drop jump tasks, and anticipated and unanticipated change of direction tasks. A full description of the testing protocol is given in (King et al., 2018).
Marker trajectory and force data were filtered using a fourth-order zero-lag Butterworth filter (cut-off frequency 15 Hz). The Inverse kinematics problem was solved as a global optimization problem. Muscle forces and contributions were attained through OpenSim (Delp et al., 2007). A 12 segment, 29 degrees of freedom musculoskeletal model was used to create the simulation. The model was manually scaled to match each subject's anthropometry using previously attained scale factors for the model segments. A residual reduction algorithm (RRA) step was implemented to minimize errors related to kinematic inconsistencies and modelling assumptions. The adjusted model and kinematic data were used for estimating muscle forces during the different movements using the Computed Muscle Control (CMC) optimization method (Thelen & Anderson, 2006). CMC uses a proportional derivative controller to provide kinematics feedback to adjust model position during the simulation and accounts for the muscle force-length–velocity properties. Based on the CMC results, an induced acceleration analysis was performed, allowing the mathematical prediction of the mechanical contribution of each individual muscle force obtained to the ground reaction forces. A rolling constraint without slipping was inserted in this analysis to substitute the interaction of the musculoskeletal model with the surrounding environment (Hamner, Seth, Steele, & Delp, 2013). A full description of this final step is given in (Mateus, Ferrer-Roca, João, & Veloso, 2020).
.
RESULTS: The main mean individual muscle contributions to the ground reaction forces for all the tasks performed are presented in Figure 1. Only the portions of the tasks where the subject was in contact with the force plate were considered for this section.

DISCUSSION: This work aimed to estimate individual muscle contributions to the ground reaction forces, via a musculoskeletal modelling approach. The main contributing muscles to the ground reaction forces are the ones that are commonly related to ACL loading (Peel, Schroeder, & Weinhandl, 2021). This work presents an innovative approach to better understand neuromuscular function after ACLR so that injury rehabilitation programmes are more robust.
All the movements produced upwards directed ground reaction forces along with the vertical directions, with single leg movements generating larger forces. Along with the anterior/posterior and mediolateral directions, only the anticipated and unanticipated cutting tasks produced relevant forces, being posteriorly and medially directed. Especially during the anticipated and unanticipated cutting tasks, it is possible to observe that, whilst performing the previously mentioned movements with the healthy lower limb, larger ground reaction forces are produced, when compared to the ACLR lower limb, thus concluding that, after ACLR, discrepancies between lower limbs arise, which in accordance to the work of (King et al., 2018). Similar observations were found during gait, in the work of (Mantashloo, Letafatkar, & Moradi, 2020).
Along the anterior/posterior direction, the quadriceps were the main contributors during all the tasks, providing support against and braking the body forward momentum, counteracted by muscle contributions from the soleus, *gastrocnemii*, and hamstrings, possibly preventing the anterior translation of the tibia. During anticipated and unanticipated cutting tasks, *gluteus maximus* also produced relevant contributions to the anterior/posterior ground reaction forces, which may be explained by its role in stabilizing trunk motion. Similar findings were observed in different movements, such as a forward braking and backward acceleration task (Mateus et

al., 2020). Along the vertical direction, the quadriceps, along with the soleus, *gastrocnemii,* and *gluteus maximus*, work to support the body against the effect of gravity. These contributions are counteracted by the tibialis anterior and the hamstrings, albeit during anticipated and unanticipated cutting tasks, the hamstrings work along with the main knee extensors and ankle plantar flexors to further support the body against gravity. This differs from the findings of (Maniar, Schache, Cole, & Opar, 2019), where muscle contributions to the ground reaction forces during a sidestep cutting task were estimated, and the hamstrings produced no contribution to the vertical ground reaction forces. Although a plausible explanation to this stems from different musculoskeletal and foot-ground contact models being implemented in both works, the findings from our work warrant further research on the hamstrings' role during anticipated and unanticipated cutting tasks in professional athletes. Along the mediolateral direction, muscles mostly showed larger contributions during planned and unplanned cutting tasks. Muscles like the *gluteus medius*, quadriceps, soleus and *gastrocnemii* acted to direct the centre-of-mass towards the course of travel through their contribution to the mediolateral GRF. These findings are per the ones found in (Maniar et al., 2019).

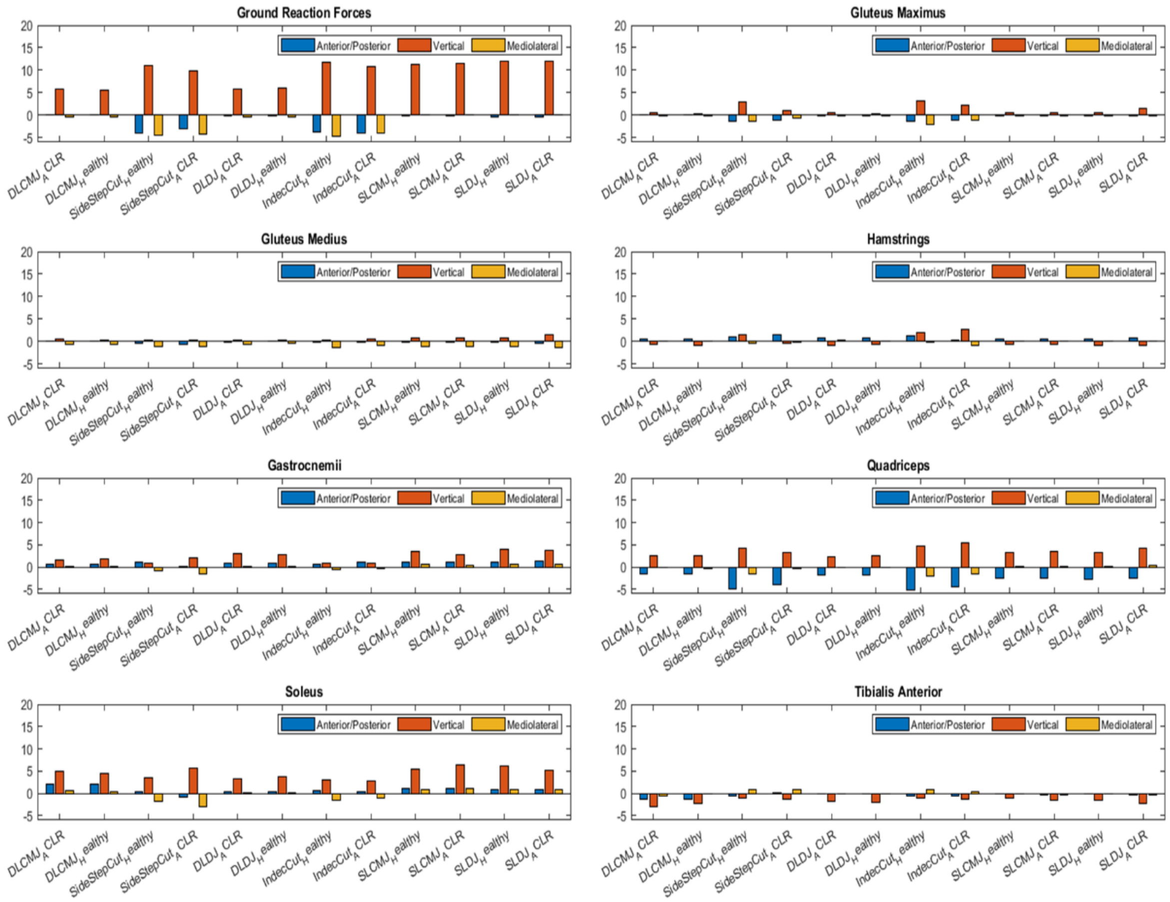

Figure 1: Main muscle contributors to the ground reaction forces along all three directions. Mean muscle contributions are given in N/Kg. Anterior (+)/Posterior(-); Upward(+)/Downward(-);Lateral(+)/Medial(-). DL – Double leg; SL – Single leg; CMJ - countermovement jump; DJ – Drop Jump; SideStepCut – Planned sidestep cut; IndecCut – Unplanned sidestep cut.

CONCLUSION: This work identified individual muscle contributions to the ground reaction forces, where the main contributors are also the main muscles acting to load the ACL, however these contributions are shown to be dependent on the type of task performed, and require further work with a larger sample size to better understand how muscles contribute to the ground reaction force during each task. Nonetheless, it gives us confidence in the implementation of such tasks in testing and recovery protocols with the intent of revealing potential ACL limitations in professional athletes.

REFERENCES

Badawy, C. R., Jan, K., Beck, E. C., Fleet, N., Taylor, J., Ford, K., & Waterman, B. R. (2022). Contemporary Principles for Postoperative Rehabilitation and Return to Sport for Athletes Undergoing Anterior Cruciate Ligament Reconstruction. *Arthroscopy, Sports Medicine, and Rehabilitation*, 4(1), e103–e113.

Delp, S. L., Anderson, F. C., Arnold, A. S., Loan, P., Habib, A., John, C. T., … Thelen, D. G. (2007). OpenSim: Open-source software to create and analyze dynamic simulations of movement. *IEEE Transactions on Biomedical Engineering*, 54(11), 1940–1950.

H, M. M., Shahrbanian, S., & Khoshroo, F. (2018). Epidemiology and history of knee injury and its impact on activity limitation among football premier league professional referees. *Journal of Injury and Violence Research*, 10(1), 45–52.

Hamner, S. R., Seth, A., Steele, K. M., & Delp, S. L. (2013). A rolling constraint reproduces ground reaction forces and moments in dynamic simulations of walking, running, and crouch gait. *Journal of Biomechanics*, 46(10), 1772–1776.

Harper, D. J., Cohen, D. D., Rhodes, D., Carling, C., & Kiely, J. (2021). Drop jump neuromuscular performance qualities associated with maximal horizontal deceleration ability in team sport athletes. *European Journal of Sport Science*, 0(0), 1–16.

Hughes, G., Musco, P., Caine, S., & Howe, L. (2020). Lower limb asymmetry after anterior cruciate ligament reconstruction in adolescent athletes: A systematic review and meta-analysis. *Journal of Athletic Training*, 55(8), 811–825.

King, E., Richter, C., Daniels, K. A. J., Franklyn-Miller, A., Falvey, E., Myer, G. D., … Strike, S. (2021). Biomechanical but Not Strength or Performance Measures Differentiate Male Athletes Who Experience ACL Reinjury on Return to Level 1 Sports. *American Journal of Sports Medicine*, 49(4), 918–927.

King, E., Richter, C., Franklyn-Miller, A., Daniels, K., Wadey, R., Moran, R., & Strike, S. (2018). Whole-body biomechanical differences between limbs exist 9 months after ACL reconstruction across jump/landing tasks. *Scandinavian Journal of Medicine and Science in Sports*.

Maniar, N., Schache, A. G., Cole, M. H., & Opar, D. A. (2019). Lower-limb muscle function during sidestep cutting. *Journal of Biomechanics*, 82, 186–192.

Mantashloo, Z., Letafatkar, A., & Moradi, M. (2020). Vertical ground reaction force and knee muscle activation asymmetries in patients with ACL reconstruction compared to healthy individuals. *Knee Surgery, Sports Traumatology, Arthroscopy*, 28(6), 2009–2014.

Mateus, R. B., Ferrer-Roca, V., João, F., & Veloso, A. P. (2020). Muscle contributions to maximal single-leg forward braking and backward acceleration in elite athletes. *Journal of Biomechanics*, 112.

Mokhtarzadeh, H., Yeow, C. H., Hong Goh, J. C., Oetomo, D., Malekipour, F., & Lee, P. V. S. (2013). Contributions of the Soleus and Gastrocnemius muscles to the anterior cruciate ligament loading during single-leg landing. *Journal of Biomechanics*, 46(11), 1913–1920.

Nasseri, A., Lloyd, D. G., Bryant, A. L., Headrick, J., Sayer, T. A., & Saxby, D. J. (2021). Mechanism of Anterior Cruciate Ligament Loading during Dynamic Motor Tasks. *Medicine & Science in Sports & Exercise*, 53(6), 1235–1244.

Padua, D. A., & DiStefano, L. J. (2009). Sagittal plane knee biomechanics and vertical ground reaction forces are modified following ACL injury prevention programs: A systematic review. *Sports Health*, 1(2), 165–173.

Peel, S. A., Schroeder, L. E., & Weinhandl, J. T. (2021). Lower extremity muscle contributions to ACL loading during a stop-jump task. *Journal of Biomechanics*, 121, 110426.

Petersen, W., Taheri, P., Forkel, P., & Zantop, T. (2014). Return to play following ACL reconstruction: a systematic review about strength deficits. *Archives of Orthopaedic and Trauma Surgery*, 134(10), 1417–1428.

Scott, K., Robinson, M. A., & Daniels, K. (2020). Comparison of Plug-in Gait and a Six Degrees of Freedom Model on Estimating Knee Kinematics During a Double Leg Drop Jump. *ISBS Proceedings Archive*, 38(1), 692.

Thelen, D. G., & Anderson, F. C. (2006). Using computed muscle control to generate forward dynamic simulations of human walking from experimental data. *J Biomech*, 39(6), 1107–1115.

ACKNOWLEDGEMENTS: The authors would like to thank and acknowledge the staff at the Sport Surgery Clinic, Dublin for their support, especially the Biomechanics team. This work was supported by CIPER-FCT (I&D unit 447, project reference UIDB / 00447/2020), and FCT (Ph.D. grant reference DFA/BD/7356/2020).