Effect of ACL Injuries on Adjacent Ligament Tensions during Level Walking

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Summary

This study quantified ligament tensions and joint contact forces in cases of anterior cruciate ligament (ACL) and antero-lateral ligament (ALL) ruptures using forward dynamics simulations of a musculoskeletal model with six-degrees of freedom (DOF) knee joints and 14 ligaments. Simulations revealed that ACL and/or ALL deficiencies significantly increased adjacent ligament tensions and joint contact forces during the stance phase. These findings highlight the biomechanical importance of combined ACL and ALL reconstruction in reducing re-rupture rates and improving joint stability during gait.

Introduction

Ligaments provide stability to joints. Their mechanical properties vary depending on their locations and the conditions within the joint [1]. Injuries to the ACL are frequently reported to accompany ALL injuries [2]. Previous studies have reported degenerative changes in articular cartilage and meniscus [3]. However, the effects of these injuries on adjacent ligament tensions and joint contact forces remain poorly quantified, despite their important role in understanding secondary injuries within the joint. Dynamic simulations of anatomical knee models provide valuable insights into injury mechanisms and facilitate the determination of optimal surgical treatments [4]. This study aims to quantify knee ligament tensions and articular contact forces under isolated and combined ruptures of the ACL and ALL during walking through forward dynamics simulations.

Methods

A musculoskeletal model with 25-DOF and 92 lower-limb muscles, originally featuring 1-DOF knee joints [5], was modified to include six-DOF knee joints. Each knee joint included 14 ligaments and 31 bundles, such as the ACL, ALL, lateral collateral ligament (LCL), medial collateral ligament (MCL), and posterior cruciate ligament (PCL). Ligament attachment points and mechanical properties were obtained from a previous cadaveric study [6] and optimized using the covariance matrix adaptation evolution strategy to replicate kinematic responses observed under external loading conditions in a prior study [7]. Gait data were collected from five healthy male participants (22.8±1.6 years, 1.71±0.04 m, 69.1±5.4 kg) following IRB approval and informed consent. A gait controller for forward dynamics simulation of the intact knee model (INTACT) was developed using a deep neural network. The network was trained using reinforcement learning to replicate the gait patterns of individual participants. Injuries were simulated for three models: ACL deficiency (ACLD), ALL deficiency (ALLD), and combined ACL and ALL deficiencies (BOTHD). Tensions in the LCL, MCL, and PCL, along with knee articular contact forces, were estimated throughout the gait cycle for each injury model. Statistical differences in ligament tensions and contact forces were evaluated using paired t-tests, with significance set at $p < 0.05$.

Results and Discussion

Our analyses focused on the stance phase of gait. Deficiencies in the ACL and/or ALL significantly increased tensions in adjacent ligaments (Table 1). The increased tensions in the LCL and MCL led to higher contact forces. Specifically, the ALLD model exhibited increased LCL tension compared to the INTACT model.

Table 1: Mean (STD) force during the stance phase. (* indicates a significant difference compared to the intact model at $p<0.05$)

Force (BW)	INTACT	ACLD	ALLD	BOTHD
LCL	0.07(0.02)	0.09(0.01)	0.12(0.02)*	0.12(0.02)
MCL	0.19(0.02)	0.25(0.04)*	0.24(0.03)*	0.20(0.03)
PCL	0.02(0.03)	0.02(0.02)	0.03(0.02)	0.02(0.02)
Contact Force	2.41(0.39)	2.69(0.44)	2.22(0.39)	3.30(0.40)*

Conclusions

An increase in joint contact force has been correlated with the development of medial knee osteoarthritis [8]. Patients with isolated ACL reconstruction show higher re-rupture rates and lower return-to-sport rates compared to those receiving ACL and ALL combined reconstruction [9]. Simulation results support the effectiveness of combined reconstruction over isolated ACL reconstruction in patients with concurrent ACL and ALL injuries.

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References

[1] Rudolph et al. (1998). *Univ Delaware*. [2] Katz et al. (1986) *Am J Sports Med* 14: 88-91 [3] Michalitsis et al. (2015) KSSTA 23:232-9 [4] Shabani et al. (2015) *Int Orthop* 39: 1187-93 [5] Rajagopal et al. (2016) *IEEE TBME* 63: 2068-79 [6] Harris et al. (2016) *J Biomh* 138: 081004 [7] Imhauser et al. (2023) *J Orthop Res* 41:2569-78 [8] Richards et al. (2018) *OARS* 26: 1203-14 [9] Sonnery et al. (2017) *Am J Sports Med* 45:1547-57

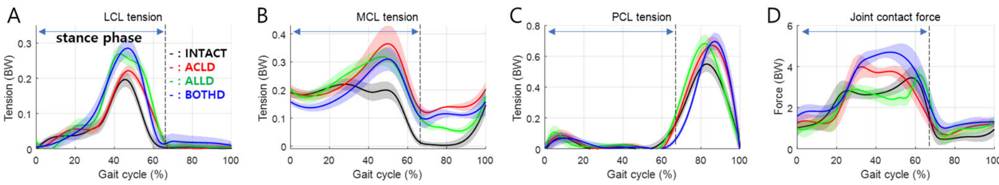

Figure 1: Tension in the LCL (A), MCL (B), PCL (C) and knee contact force (D), for the healthy and three ligament injury models