Kinematic signatures of unsupervised knee joint reaction load patterns in single-leg squats

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Summary

Are knee joint reaction load (JRL) patterns and lower limb kinematics related? To investigate this topic, we estimated medial and lateral tibiofemoral and patellofemoral loads in OpenSim from 80 healthy participants' single-leg squats aiming for 60° knee flexion. Time series clustering of normalized JRLs revealed two load patterns. One pattern, with higher patellofemoral and total loads, was associated with greater knee flexion. The other pattern, which included 89% females, had more hip internal rotation and knee valgus alignment and extension, potentially imposing higher neuromuscular demands without increased medial loading.

Introduction

Understanding knee JRLs during movement can support prevention, rehabilitation, and performance training. While frontal plane leg alignment is commonly emphasized during training, its relationship to JRLs remains controversial. Can unsupervised learning identify patterns of knee JRLs that have distinct kinematic signatures during single-leg squats?

Methods

Eighty healthy participants performed seven left and right single-leg squats aiming for 60° knee flexion. We collected left and right force plate (AMTI) 3D ground reaction forces (GRFs) and 3D reflective marker trajectories from an adapted Cleveland Clinic marker set using 3D motion analysis (3DMA) (Vicon, Nexus 2.16). After export to OpenSim 4.5, the automatic scaling tool (constrained not to update segment lengths) scaled the Lerner/Rajagopal lower body model [2] to root mean square errors (RMSE) < 0.4 cm [1], fitted inverse kinematics to RMSE <2 cm and max error <4 cm, performed static optimization with squared sum of muscle activation costs, and estimated medial and lateral tibiofemoral and patellofemoral JRLs. Standing pose 3DMA direct kinematic knee flexion, adduction, and hip rotation angles, measured height, and weight informed scaling. We adjusted any muscle path wrapping object that caused muscle moment arm inconsistencies across all dynamic trials. A custom script based on knee flexion angle velocity defined squat down, transition, and up phases, but inhomogeneous transitions required manual checks. Cubic splines interpolated the squat-down phases to 101 frames. We computed the resultant of each JRL, normalized it to body weight (BW), and scaled it to equal mean and variance for dynamic time warping time series k-means clustering with k = 2, 3, 4. The silhouette score (SIL) evaluated cluster separation. 1D statistical parametric mapping one-way ANOVA for the sagittal, frontal, and transverse planes of the thorax and pelvis and the hip, knee, and ankle angles of the active leg and the three JRL features assessed differences across squat down cycles (not all shown), the Kruskal-Wallis test compared JRL and angle means (both Bonferroni-corrected $p_{crit.} = 0.0028$).

Results and Discussion

Squat-down cycles of 36 females and 19 males were valid for clustering (Table 1). We selected the moderate $SIL(k_2) = 0.28$ over $SIL(k_3) = 0.16$ and $SIL(k_4) = 0.11$. Cluster A represented 54% and Cluster B 89% females. The two knee JRL patterns and joint angle profiles had different means over time ($p<p_{crit.}$, Figure 1). While the maximum JRL values did not differ between clusters over time, the means did ($p<p_{crit.}$). The patellofemoral JRL sample mean (standard deviation) of Cluster A was 4.8 (0.8) vs. 4.0 (0.8) BWs in Cluster B, the total tibio-femoral JRL of Cluster A was 8.2 (0.9) vs. 7.9 (0.8) BWs. In Cluster B, the hip joints were on average 4.4° (0.6°) more internally rotated and the knee joints were 4.3° (0.8°) more extended and 1.5° (0.5°) more valgus than in Cluster A, which likely underestimates the absolute difference. While the slightly less skeletally supported leg alignment of Cluster B may not be clinically significant across repetitions, in-depth analysis should evaluate the individual at the time series level.

Table 1: Participant means and standard deviations per cluster with counts of single-leg squat repetitions (n) of females (f) & males (m).

	Cluster A	Cluster B
Height in m	1.708 (0.088)	1.736 (0.074)
BMI	23.2 (2.4)	23.0 (2.2)
Age in yrs	31.9 (12.0)	36.3 (14.1)
Counts	n=325, f=20, m=17	n=183, f=16, m=2

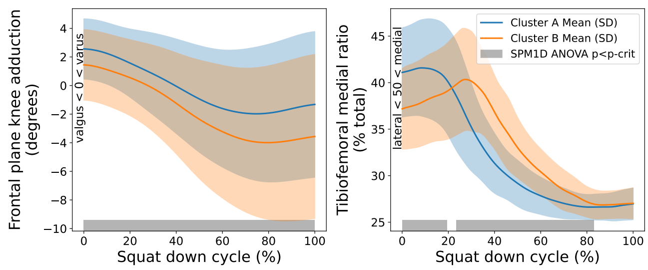

Figure 1: Direct kinematic frontal plane angle & knee medial compartment JRL ratio differ between JRL patterns.

Conclusions

Despite controlled exercise conditions, unsupervised clustering of knee JRLs during single-leg squats revealed two distinct patterns. While slightly higher patellofemoral and total JRLs occurred with greater knee flexion, hip internal rotation and knee valgus did not increase medial loads. Further investigation of these patterns in additional exercises and situations that challenge frontal leg alignment with personalized musculoskeletal models that account for sex differences should test the robustness of these findings.

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References

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