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Improvements in medial knee contact force predictions through synergistic muscle recruitment

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INTRODUCTION

Musculoskeletal modeling has increasingly becoming an essential tool in orthopedic biomechanics. Model predictions have been used to improve locomotion and overall quality of life of individuals presenting musculoskeletal disorders and also for those undergoing major interventions such as knee implants. Predicting internal forces on the knee during locomotion is crucial to the successful implementation of musculoskeletal modeling onto real-world scenarios. This topic is of such importance that a worldwide biomechanics competition has been established in the past to promote advances on internal forces prediction (the Grand Challenge Competition to Predict in Vivo Knee loads [1]).

The control of human locomotion is achieved by a complex interaction between central and peripheral inputs to the muscles. During walking, it has been shown that neural control of gait can be described by a low-dimensional set of synergistic activation patterns (called muscle synergies or motor modules) [2]. Therefore, implementing musculoskeletal modeling approaches to predict lower limb joint internal forces may be optimized through the inclusion of synergy control for the muscles.

Therefore, the purpose of this study was to predict internal knee forces from the Fifth Grand Challenge Competition to Predict in vivo Knee Loads by adding muscle weighting coefficients to the musculoskeletal model. It was hypothesized that knee internal forces prediction could be optimized by adding a synergistic characteristic for the muscle recruitment.

METHODS

Experimental data from the Fifth Grand Challenge Competition to Predict in vivo Knee Loads [1] were used for this study. The data were collected from a single male subject implanted with a force-measuring knee replacement (age: 86, height: 1.8 m, and body mass: 75kg). The patient performed overground walking trials at a self-selected speed while marker trajectory, ground reaction force and moment, EMG, and knee implant load data were collected simultaneously. CT data were also collected. EMG data were collected from 13 muscles including the tibialis anterior, peroneus longus, soleus, gastrocnemius lateralis and medialis, vastus lateralis and medialis, rectus femoris, semimembranosus, biceps femoris, gluteus maximus, adductor magnus and tensor fascia latae.

EMG processing. We band-pass (zero-lag fourth-order Butterworth at from 10 to 400 Hz), full-wave rectified, and low-pass filtered (zero-lag fourth order Butterworth at 6 Hz) the EMG data. Subsequently, we applied non-negative matrix factorization (NMF) [3] on the EMG envelopes following procedures described elsewhere [4,5]. For this study, we predicted the knee contact forces using four, six and eight synergies. The variance accounted for (VAF) were 86% for four synergies (low reconstruction quality), 92% for six synergies (ideal number of synergies for this analysis) and 96% for eight synergies (higher reconstruction quality) across all muscles. We used the muscle weightings from these sets of synergies to define synergy controls for these muscles.

Knee contact forces. We applied the previously developed musculoskeletal model by Marra et al. [6] developed in the AnyBody Modeling System (AnyBody Technology, Denmark) as the foundation of this study. This is a patient-specific model created based on the CT data and includes an 11 degree of freedom Force-dependent Kinematics knee model. To estimate muscle forces, this model relies on a muscle recruitment criteria and in this study, we included the muscle synergies. To this end, we created constraints between the muscle forces according to the identified muscle synergies and applied the model to estimate the total, medial and lateral knee contact forces.

We computed the Pearson's correlation coefficient, root means square error (RMSE) and relative root mean square error (rRMSE) between the experimental forces (total, medial and lateral knee forces) with respect to the estimated knee forces generated without the synergy control (NoSyn), as well as using four (4Syn), six (6Syn) or eight synergies (8Syn).

RESULTS AND DISCUSSION

The experimental and estimated knee internal forces are illustrated in Figure 1. Estimating joint forces using 4Syn, 6Syn and 8Syn substantially reduced the second peak on the total, medial and lateral forces in comparison to the forces generated from NoSyn estimation. Consequently, the second peak from the experimental and estimated forces were closer for the total force and medial forces. Moreover, there was a slight increase in Pearson's correlation, and reductions in RMSE and rRMSE (~3%) for the medial force estimation when using synergy controls (Table 1).

Conversely, the second peak in the lateral force was substantially suppressed when using synergy controls. Subsequently, the errors increased in comparison to NoSyn estimation for all parameters (Table 1). There was no conclusive data to establish that the number of synergies have an influence in the quality of the internal forces prediction. This fact may be partially explained by the relatively high VAF achieved with four synergies (0.86), which may already provide an optimal balance of synergistic muscle activation across all 13 muscles investigated. Previous studies have demonstrated improvements on estimating internal joint forces during walking in similar experimental conditions [7]. However, further research is necessary to further implement EMG-based parameters to optimize joint force estimations in walking and other daily life motor tasks.

CONCLUSIONS

In conclusion, the use of EMG-based synergy control for the estimation of internal knee forces during walking improved the estimation of the medial forces, but not for the total and lateral forces. Moreover, the number of modules used to establish the synergy control does not pose a substantial influence on the force estimations.

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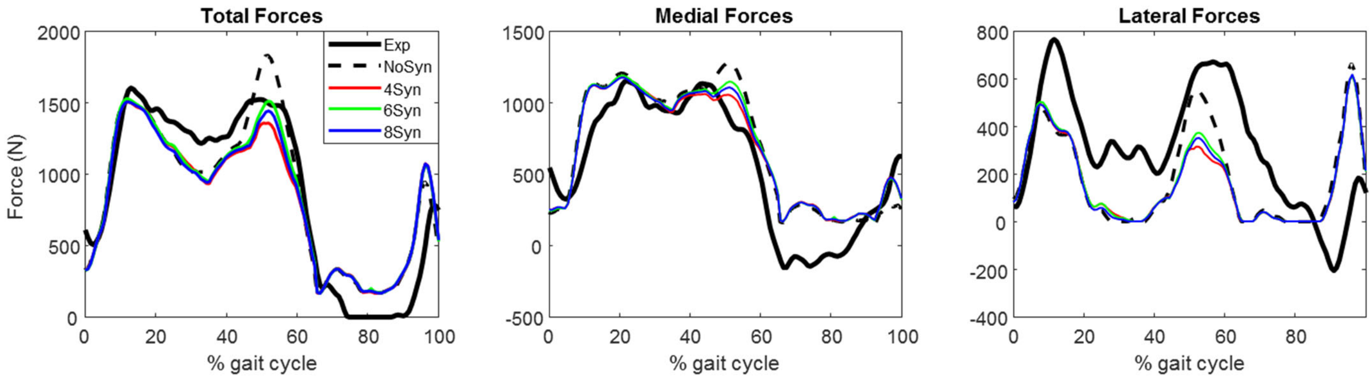

Figure 1. Knee internal forces during one gait cycle expressed as total forces (*left panel*), medial forces (*central panel*) and lateral forces (*right panel*) for the experimental data (black solid lines), predicted forces without synergy control (NoSyn, *black dashed lines*) and predicted forces with synergy control from four (*red*), six (*green*) and eight synergies (*blue*).

Table 1. Pearson's correlation coefficient, root mean square error (RMSE) and relative RMSE between experimental internal knee forces and the estimated forces without (NoSyn) and with synergy controls (4Syn, 6Syn and 8Syn).

	Pearson correlation (r)			RMSE (N)			Relative RMSE (%)		
	Total	**Med**	**Lat**	**Total**	**Med**	**Lat**	**Total**	**Med**	**Lat**
NoSyn	0.95	0.91	0.46	198.40	232.96	263.53	22.46	33.68	137.60
4Syn	0.95	0.93	0.39	225.86	206.93	278.90	27.02	30.81	169.71
6Syn	0.95	0.93	0.43	209.78	216.70	271.12	24.45	31.55	158.44
8Syn	0.95	0.93	0.41	219.58	208.73	277.15	26.06	30.83	167.37