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Practical approach to subject-specific estimation of knee joint contact force

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ABSTRACT

Compressive forces experienced at the knee can significantly contribute to cartilage degeneration. Musculoskeletal models enable predictions of the internal forces experienced at the knee, but validation is often not possible, as experimental data detailing loading at the knee joint is limited. Recently available data reporting compressive knee force through direct measurement using instrumented total knee replacements offer a unique opportunity to evaluate the accuracy of models. Previous studies have highlighted the importance of subject-specificity in increasing the accuracy of model predictions; however, these techniques may be unrealistic outside of a research setting. Therefore, the goal of our work was to identify a practical approach for accurate prediction of tibiofemoral knee contact force (KCF). Four methods for prediction of knee contact force were compared: (1) standard static optimization, (2) uniform muscle coordination weighting, (3) subject-specific muscle coordination weighting and (4) subject-specific strength adjustments. Walking trials for three subjects with instrumented knee replacements were used to evaluate the accuracy of model predictions. Predictions utilizing subject-specific muscle coordination weighting yielded the best agreement with experimental data; however this method required in vivo data for weighting factor calibration. Including subject-specific strength adjustments improved models' predictions compared to standard static optimization, with errors in peak KCF less than 0.5 body weight for all subjects. Overall, combining clinical assessments of muscle strength with standard tools available in the OpenSim software package, such as inverse kinematics and static optimization, appears to be a practical method for predicting joint contact force that can be implemented for many applications.

1. Introduction

Compressive forces experienced at the knee can have significant impact on cartilage degeneration and contribute to the initiation and progression of osteoarthritis (Blagojevic et al., 2010; Felson et al., 1988). As knee osteoarthritis progresses, causing pain and reduced function, the only effective treatment is knee arthroplasty, a costly and intensive procedure. Compressive forces continue to be relevant and arguably more important following knee arthroplasty, as these forces influence the wear, and therefore lifetime, of the implant. Subject-specific factors such as age, sex, body mass index and strength influence disease progression and are likely related to the magnitude of the knee loads which may be useful in the design of a treatment plan.

Traditionally, external knee loads have been used to estimate internal tibiofemoral knee contact forces (KCF) (Komistek et al., 2005); however it has been suggested more recently that external loads and electromyography are not good indicators of changes in knee contact forces (Meyer et al., 2013). The use of musculoskeletal models enables predictions of the internal forces experienced at the knee, namely the muscle, ligament and articular contact forces. Given the advantage of modeling for assessing knee loading, the accurate prediction of compressive force at the knee through musculoskeletal modeling can be a useful tool for understanding the mechanisms behind joint loading. Validating model results, however, is often not possible, as experimental data detailing loading at the knee joint is limited. Recently available data which directly measures compressive knee force using instrumented total knee replacements offer a unique opportunity to evaluate the accuracy of models.

Several groups have reported good agreement of model predicted knee compressive force with experimentally measured data, using a variety of methods (Kinney et al., 2013). Steele et al. (2012) used a weighted static optimization technique to find the optimal match

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between experimental (as measured by an instrumented knee implant) and simulated knee joint contact force (Steele et al., 2012). Using this technique, weighting constants for the quadriceps, hamstrings, and plantar flexor muscle groups were included to alter the distribution of muscle activations during the simulation, resulting in a 20% body weight difference between the peak experimental and model-predicted knee compressive force. However, the validation performed in this study focused on only one subject and it is unclear whether this method would result in similar accuracy when applied across multiple individuals. Other methods utilized subject-specific measurements included alongside the experimental knee contact force data to enhance the accuracy of model predictions. These subject-specific measurements include subject-specific geometry data obtained from CT scans (Gerus et al., 2013), or electromyography (EMG) measured during experimental collections (Manal and Buchanan, 2013; Hast and Piazza, 2013).

These previous studies have highlighted the importance of subject-specificity in increasing the accuracy of model predictions. These techniques, however, involve time-intensive data collection and processing, as well as access to expensive equipment and resources for imaging that may be unrealistic outside of a research setting. In addition, these techniques often employ complex models or algorithms that are not readily available outside research settings (Manal and Buchanan 2013; Lundberg et al., 2013; Hast and Piazza 2013). In contrast to the prohibitive nature of some subject-specific measurements and techniques involving EMG or imaging, measurements involving maximum muscle strength are readily attainable in a clinical or research setting. Strength data has been shown to be related to multiple variables than can be influential when considering a subject's gait such as walking speed, gender and age (Berger et al., 2012; Aagaard et al., 1997), and pain and function in knee osteoarthritis (O'Reilly et al., 1998). While it is unclear whether strength and joint contact force are directly correlated, it is possible that muscle strength influences knee joint contact force through its relationship with many gait related factors. Furthermore, the likelihood of a muscle to be recruited should be related to its strength, and should directly affect model predictions. Indeed, previous work has shown that simulated atrophy and activation failure in muscle groups can alter model predictions of muscle activations (Thompson et al., 2013; Knarr et al., 2013) and the use of experimentally measured, subject-specific muscle force data has shown increased accuracy of muscle activation predictions in other populations such as stroke (Knarr et al., 2014).

The importance of including subject-specific parameters into model predictions of knee joint contact force has been demonstrated in many recent studies; however previously reported methods have been either limited in scope or prohibitively complex to implement in common clinical settings. Therefore, the goal of our work was to identify a practical approach which enables accurate predictions of knee joint contact force without prohibitively increasing the complexity of the methodology. In this study we identified and evaluated four approaches for improving predictions of knee joint compressive force: (1) standard static optimization, (2) uniform muscle coordination weighting, (3) subject-specific muscle coordination weighting, and (4) subject-specific strength adjustments.

2. Methods

Three dimensional simulations were created from the stance phase of gait for 3 subjects with an instrumented knee implant using OpenSim 3.0.1 (Delp et al., 2007) (Table 1). Subject data were collected and distributed as part of the first three years of the Grand Challenge Competition to predict in vivo knee loads (Fregly et al., 2012) (Table 1). The implant was instrumented with either four uniaxial force transducers, one each in the four quadrants of the tibial tray, or a six-axis load cell in the stem of the tibial tray, with load cell measurements telemetered using a micro-transmitter and antenna. A previously developed musculoskeletal model of the lower body and torso was used, which included 92 actuators, with three degrees of freedom at the pelvis–torso and hip joints, and one degree of freedom at the knee, ankle and toe joints (Demers et al., 2014) (Fig. 1). In addition, the model includes a frictionless patella which articulates with the femur as prescribed by knee angle and directs the quadriceps forces along the patellar ligament (Demers et al., 2014). Two to four walking trials were used for each subject, resulting in 10 total walking trials. All analysis was focused on the limb with the instrumented knee.

Table 1
Subject demographics, uniform and subject-specific weighting coefficients, and error between experimental and simulated joint contact forces. Errors expressed in terms of root mean squared error (RMSE), as well as first and second peak errors relative to body weight (BW) for four methods: standard optimization (SO), uniform weighting (UW), subject-specific weighting (SSW) and subject-specific strength (SSS). See the text for details.

		Subject 1	Subject 2	Subject 3
Gender		M	M	F
Height (m)		1.66	1.72	1.67
Weight (kg)		64.6	67	78.4
Knee		R	R	L
Uniform weights	PF	7	7	7
	H	3	3	3
	Q	1	1	1
Subject-specific weights	PF	2	2	1
	H	6	10	1
	Q	3	6	3
RMSE (BW)	SO	0.67	0.59	0.37
	UW	0.43	0.48	0.48
	SSW	0.34	0.41	0.33
	SSS	0.40	–	0.37
Peak 1 error (BW)	SO	0.56	0.95	0.14
	UW	0.31	0.62	0.39
	SSW	0.11	0.22	0.24
	SSS	0.10	–	0.24
Peak 2 error (BW)	SO	1.37	0.83	0.40
	UW	0.59	0.46	0.74
	SSW	0.01	0.15	0.09
	SSS	0.42	–	0.33

Inverse kinematics was used to determine the model joint kinematics which creates a model position that best matches experimental data. Kinematics and kinetic data were filtered at 6 Hz. Simulations were created from heel strike to toe off of the instrumented limb and all data was reported for the instrumented limb. Four methods for prediction of knee joint contact force were compared.

2.1. Static optimization

The muscle forces required to reproduce the measured kinematics and kinetics were calculated using static optimization in OpenSim with the default cost function minimizing the sum of the activations squared (Delp et al., 2007). Knee joint contact force was calculated using the muscle force results from static optimization using the joint reaction force tool in OpenSim and expressed in the tibial reference frame. Resultant knee contact forces were filtered at 10 Hz to minimize influence of high frequency changes in force during weight acceptance (prior to the first peak in KCF), arising from the discrete static optimization solution. Filtering was performed because high frequency changes were not present in the experimentally measured data, which may be dampened by soft tissue or filtered during processing.

2.2. Muscle coordination weighting: uniform and subject-specific

A weighted static optimization technique similar to Steele et al. (2012) was used to find the optimal match between experimental (as measured by the instrumented knee) and simulated knee joint contact force (Steele et al., 2012). Using this technique, weighting constants for the quadriceps, hamstrings, and plantar flexor muscle groups were included to alter the distribution of muscle activations during the simulation.

To investigate the generalizability of applying uniform muscle coordination weight across subjects to produce accurate predictions of knee contact forces during stance, two simulations were created per subject. The first simulation used the reported values for weighting constants for a single subject from previous literature (Steele et al., 2012). This method allows us to investigate the generalizability of weighting constants across additional subjects and trials. For the second simulation, subject-specific weighting constants were determined using an optimization technique. While performing a subject-specific optimization using in vivo data is unlikely to be a practical and widely applicable methodology, it provides us with a "best case" scenario with which to compare the other, more generalizable