The Knee 22 (2015) 481–489

Contents lists available at ScienceDirect

The Knee

Joint contact forces when minimizing the external knee adduction moment by gait modification: A computer simulation study

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ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form 12 May 2015
Accepted 23 June 2015

Keywords:
Gait modification
Knee adduction moment
Joint contact force
Simulation
Minimization

ABSTRACT

Background and purpose: Gait modification is often used to reduce the external knee adduction moment (KAM) in human walking, but the relationship between KAM reduction and changes in medial knee joint contact force (JCF) is not well established. Our purpose was to examine the limiting case of KAM-based gait modification: reducing the KAM as much as possible, and the resulting effects on JCF.
Methods: We used musculoskeletal modeling to perform three optimal control simulations: normal walking, a modified gait that reduced the KAM as much as theoretically possible (Min(KAM) simulation), and a second modified gait that minimized the KAM plus the metabolic cost of transport (Min(KAM+CoT) simulation).
Results: The two modified gaits both reduced the peak KAM from normal walking (−82% for Min(KAM) simulation, −74% for Min(KAM+CoT) simulation) by increasing trunk lean, toe-out, and step width, and reducing knee flexion. Even though the Min(KAM+CoT) simulation had the larger KAM, it had a greater reduction in peak medial JCF (−27%) than the Min(KAM) simulation (−15%) because it reduced the KAM using less knee muscle activity. These results were qualitatively robust to a sensitivity analysis of the knee joint model, but the magnitude of changes varied by an order of magnitude.
Conclusions: The results suggest that (i) gait modification can benefit from considering whole-body motion rather than single adjustments, (ii) accurate interpretation of KAM effects on medial JCF requires consideration of muscle forces, and (iii) subject-specific knee models are needed to accurately determine the magnitude of KAM reduction effects on JCF.

1. Introduction

The external knee adduction moment (KAM) is often interpreted as a reflection of medial knee joint loading in gait [15,33,39]. Volitional modification of gait mechanics can reduce the KAM without surgery or pharmacy, and different modifications are often ranked by their amount of KAM reduction [8,16,18]. This application of the KAM is motivated by a growing body of evidence that a relatively high KAM at baseline is associated with negative clinical outcomes and structural degeneration of the knee [2,6,9,10,22,28,34,38].

Since local mechanical loading is thought to play a major role in the osteoarthritis (OA) disease process [12,14,19], KAM-reducing gait modifications may eventually be useful for treating and preventing medial knee OA. However, a simple model of the knee (Fig. 1) suggests factors other than the KAM may contribute substantially to medial knee joint contact forces (JCF) in gait. Broadly, the generalized external forces $\mathbf{F}_{ext}$ acting on the knee equal the negation of the internal forces $\mathbf{F}_{int}$:

$$\mathbf{F}_{ext} = -\mathbf{F}_{int} \quad (1)$$

where the external forces are the resultant joint kinetics, and the internal forces are summed muscle forces, medial and lateral JCF, and other relatively small forces (e.g. ligaments) which are neglected:

$$\mathbf{F}_{ext} = -(\mathbf{F}_{mus} + \mathbf{F}_{med} + \mathbf{F}_{lat} + \cancel{\mathbf{F}}_{other}) \quad (2)$$

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http://dx.doi.org/10.1016/j.knee.2015.06.014

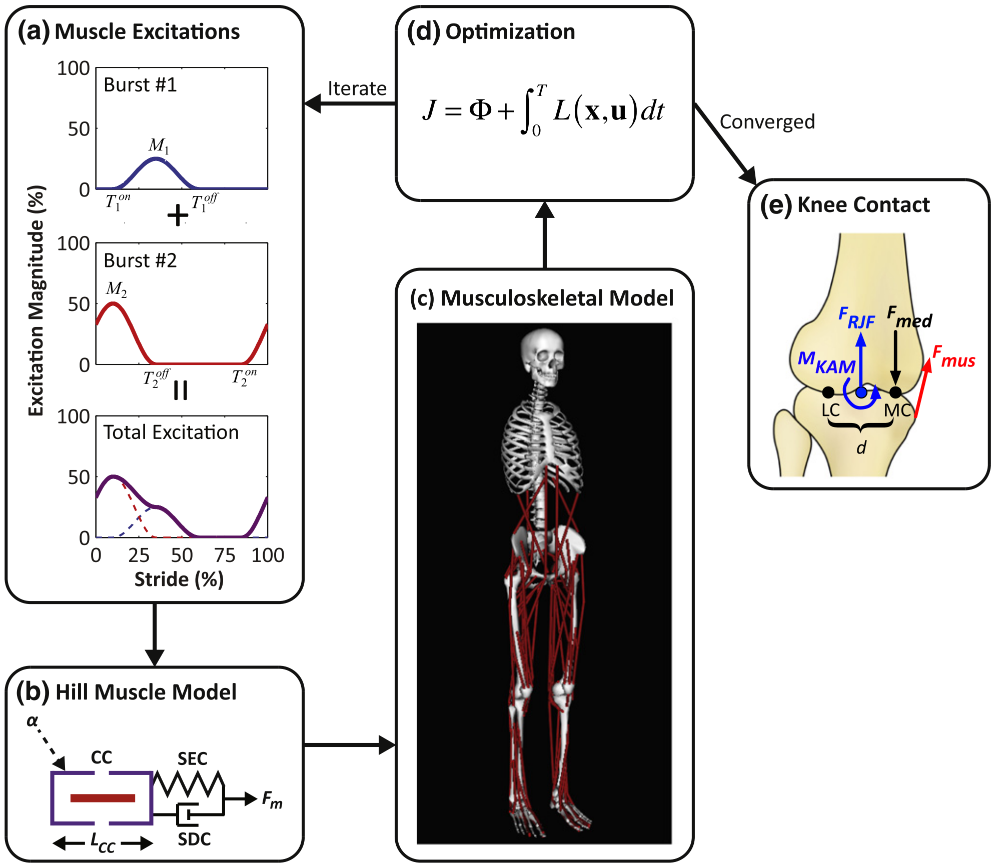

Fig. 1. Diagram of the musculoskeletal model and simulation approach. (a) Muscle excitations are defined by six parameters per muscle: two values each for M_i, T_i^{on}, and T_i^{off}. (b) Each of the 78 muscles receives an excitation defined by its six muscle-specific parameters, and develops force in response. (c) Joint moments resulting from muscle forces are applied to the skeleton to cause motion. (d) Excitations are adjusted through optimization to minimize a cost function J. (e) Following optimization, knee joint contact forces are calculated using a frontal plane equilibrium model. Ref. [50].

The medial JCF on the tibial plateau in generalized terms is then:

$$\mathbf{F}_{med} = -(\mathbf{F}_{mus} + \mathbf{F}_{lat} + \mathbf{F}_{ext}). \tag{3}$$

Applying Eq. (3) to the model in Fig. 1, the medial JCF F_{med} can be calculated by summing moments about the lateral tibiofemoral contact point in the frontal plane:

$$F_{med} = -\left(\frac{\sum_{i=1}^{n} r_i F_i}{d} + \frac{F_{RJF}}{2} + \frac{M_{KAM}}{d}\right) \tag{4}$$

where F_i and r_i are the force and moment arm of the ith knee muscle, M_{KAM} is the KAM, F_{RJF} is the resultant joint force from inverse dynamics, d is the distance between the medial and lateral contact points on the tibial plateau (F_{RJF} assumed to act midway between these points), and the negative sign indicates the contact force is compressive. Eq. (4) indicates that any changes in medial JCF will be determined not only by changes in KAM but also by muscle forces (reflected by F_i), by gait mechanics not directly affecting the KAM (reflected by F_{RJF}), and by joint anatomy (reflected by d and r_i). The effect of F_{RJF} will be relatively small since $d << 2$. However, most studies on gait modification have not considered muscle activity when inferring change in joint loading from changes in KAM.

Studies of two individuals with instrumented knee replacements have suggested factors other than the KAM in Eq. (4) are not negligible when studying gait modifications: while the KAM can reliably predict the ratio of medial/lateral JCF, reducing the KAM by gait modification often does *not* reduce the medial JCF, and may even *increase* medial JCF [31,47,52]. A larger study of nine instrumented knee subjects reported weak correlations between KAM and medial JCF magnitudes in normal walking [26]. Before gait modification can be used with confidence in practice, there is thus a need to better understand how reducing the KAM affects JCF and when (if ever) reducing the KAM necessarily indicates medial JCF have also been reduced.

In this study, we combined the frontal plane knee joint model in Fig. 1e with a full-body human musculoskeletal model [32] to examine the KAM-JCF relationship in modified walking. Modeling is useful for this purpose because it allows for (i) direct measurement of JCF, (ii) application of optimal control theory, and (iii) manipulation of joint anatomy. Our specific research questions were:

1. What is the maximum reduction in KAM that can be achieved by volitional gait modification, and how does this gait compare to normal gait?
2. Does reducing the KAM as much as possible also reduce medial JCF?
3. Do the direction and magnitude of changes in medial JCF with KAM minimization depend on joint anatomy?