PREDICTING PATIENT-SPECIFIC GAIT MODIFICATIONS FOR KNEE OSTEOARTHRITIS REHABILITATION

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1. ABSTRACT

Gait modification is a non-surgical approach for reducing the external knee adduction torque in patients with knee osteoarthritis (OA). The magnitude of the first adduction torque peak in particular is strongly associated with knee OA progression. While toeing out has been shown to reduce the second peak, no simple gait modifications have been identified that effectively reduce both peaks simultaneously. This study predicts novel patient-specific gait modifications that achieve this goal without changing the foot path. The modified gait motion was designed for a single patient with knee OA using dynamic optimization of a patient-specific, full-body gait model. The cost function minimized the knee adduction torque subject to reality constraints limiting how much the new gait motion could deviate from the patient's normal gait motion. The optimizations predicted a "medial-thrust" gait pattern that reduced the first adduction torque peak between 32 and 54% and the second peak between 34 and 56%. After gait retraining, the patient achieved adduction torque reductions of 35 to 50% in the first peak and 32 to 55% in the second one. These reductions are comparable to those reported after high tibial osteotomy surgery. This study demonstrates that it is feasible to design novel patient-specific gait modifications with potential clinical benefit using dynamic optimization of patient-specific, full-body gait models. Further investigation is needed to assess the extent to which similar gait modifications may be effective for other patients with knee OA.

2. INTRODUCTION

Despite the need for early treatment, few clinical interventions slow the progression of knee OA and minimize future functional limitations. A non-invasive early treatment option that has received limited attention is gait modification to decrease the peak knee adduction torque, which has been identified as a marker of disease progression. Ideally, if simple gait modifications could reduce the peak adduction torque by as much as high tibial osteotomy (HTO) surgery, then the benefits of the surgery could be made available to a broad clinical population without the risks and costs of an invasive

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procedure. To date, at least four basic gait modifications have been shown to reduce the adduction torque in patients with knee OA: toeing out, walking more slowly, walking with a decreased stride length, or using lateral heel wedges. Walking with the toes pointed outward can reduce the second peak of the adduction torque curve by as much as 40% but has little influence on the first peak (Andriacchi, 1994; Guo and Manal, 2006). Walking slower or with decreased stride length can reduce both peaks significantly in some patients but not others (Mündermann et al, 2004), but the speed or stride length decrease required to achieve a significant reduction may be larger than many patients would tolerate. Recent gait studies using lateral heel wedges have reported only modest reductions in the peak adduction torque (Kakihana et al., 2005). Thus, no clinically realistic gait modifications have been identified that will reduce the first peak or both peaks of the adduction torque curve to an extent comparable to HTO surgery.

This feasibility study seeks to design a novel yet “normal looking” gait motion that reduces both adduction torque peaks to the same extent as HTO surgery but without changing the foot path or trunk orientation. The design process was tailored to an individual patient, utilized dynamic optimization of a patient-specific full-body gait model, and required the patient’s pre-treatment gait data as a starting point. The optimization results were used to teach the patient how to walk differently to reduce both adduction torque peaks simultaneously. Gait data collected from the patient following gait retraining were used to evaluate the extent to which the predicted modifications can be achieved and sustained in clinical practice.

3. METHODS

3.1 Experimental data collection

Gait data were collected from a single highly functional knee OA patient (male, age 37 years, height 170 cm, mass 69 kg, alignment 5° varus with Kellgren and Lawrence grade 2 medial OA in both knees based on radiographic assessment). The subject gave informed consent and walked at a self-selected speed of 1.4 m/sec. Surface marker data using the Cleveland Clinic marker set with addition markers on the feet were collected at 120 Hz using a video-based motion analysis system (Motion Analysis Corporation, Santa Rosa, CA). A static trial with additional markers over anatomical landmarks was performed to define segment coordinate systems and marker locations within those coordinate systems. Dynamic joint motion trials were performed for the hip, knee, and ankle to exercise their primary functional axes for determination of joint positions and orientations in the segment coordinate systems (Reinbolt et al., 2005). For the gait trials, ground reaction forces and torques under each foot were measured at 1000 Hz about the electrical centers of two force plates (Advanced Mechanical Technology, Inc., Watertown, MA). The data collection and subsequent computer simulations were approved by the institutional review board. One complete gait cycle (left heel strike to left heel strike) with clean surface marker and ground reaction data was selected as the nominal data set for use in the optimization study.

After optimization predictions were developed using the patient’s nominal gait data, the patient attempted to train himself to produce the predicted gait motion. Training consisted of studying plots of the optimized kinematics, kinetics, center of pressure, and ground reactions, as well as animations comparing the nominal and optimal gait motions. After a nine-month self-training period, the patient gave informed consent and was retested under two conditions at a self-selected walking speed of 1.4 m/s. First, the patient was asked to walk using his old gait motion from prior to retraining, and second, to walk using an exaggerated version of the new gait motion predicted by the optimizations. These two walking patterns were selected to bound the experimental adduction torque changes that the patient could achieve as a result of retraining.

3.2 Dynamic model development

A parametric, three-dimensional, dynamic gait model was developed using Software for Interactive Musculoskeletal Modeling (SIMM) with the Dynamics Pipeline (Motion Analysis Corporation, Santa Rosa, CA). The SIMM/Pipeline model provided a well-structured dynamic simulation environment along with the ability to visualize the predicted motions and ground reaction force vectors using a skeletal model scaled to the patient's dimensions. The gait model possessed 27 degrees of freedom (DOFs) composed of gimbal (3 DOFs), universal (2 DOFs), and pin (1 DOF) joints (Fig. 1). All joint and inertial parameters in the model were calibrated to the patients isolated joint motion and nominal gait motion data using optimization (Reinbolt *et al*., 2005). In lieu of a deformable ground contact model utilizing springs and dampers (Anderson and Pandy, 2001), the ground reaction forces and torques calculated using the force plate electrical centers were treated as unknowns to be determined during periods when the foot was known to be in contact with the ground (Popović, 1999). This approach also eliminated the need for a toes segment in each foot model.

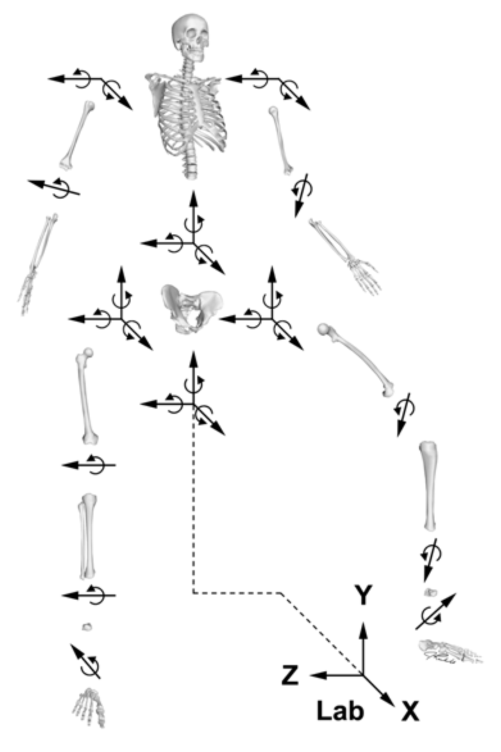

Figure 1: Schematic of patient-specific dynamic gait model used in the optimization studies.

Inverse dynamic analyses were performed using the state-space form of the equations of motion from both full-body gait models. Consequently, 27 control forces and torques were calculated from the 27 equations of motion and the experimentally determined joint kinematics and ground reaction quantities. The left external knee adduction torque was calculated as the negative of the internal reaction torque about an axis directed anteriorly through the origin of the tibial coordinate system (i.e., midpoint between the femoral epicondyles). External forces and torques acting on the pelvis were calculated from the 6 DOF joint between the ground and pelvis. Since no external loads act on the pelvis in real life, non-zero external force or torque components at any time frame represent error in the model and/or experimental data.

3.3 Dynamic optimization predictions

We used an inverse dynamic optimization approach to design "normal looking" gait motions capable of reducing both adduction torque peaks simultaneously. Rather than varying control torque inputs and predicting motion outputs using forward dynamics, our optimizations varied motion (and ground reaction) inputs and predicted control torque outputs using inverse dynamics. The design variables for the one-cycle gait optimizations were coefficients defining the shape of each motion and ground reaction input curve. Initial guesses were taken as the curves representing the patient's nominal gait data. Ground reactions were set to zero for time frames when the foot was known to be off the floor. Shoulder and elbow rotations and pelvis horizontal translations were prescribed to match the nominal gait motion.

The selected optimization cost function minimized the left and right knee adduction torques subject to several reality constraints implemented via a penalty method. The penalty terms forced the optimization to use muscle control torques similar to the nominal case, keep the center of pressure under each foot, follow the nominal foot paths and trunk orientation, and eliminate external forces and torques acting on pelvis. Two gait optimizations were performed with this cost function, with one putting more weight on minimization of knee adduction torque and less weight on tracking of leg control torques and center of pressure trajectories. Despite the use of 620 design variables, each optimization required only 45 minutes of CPU time on a 1.7 GHz Pentium M laptop.

4. RESULTS

Both optimizations predicted "normal looking" gait motions that significantly reduced both adduction torque peaks during left leg stance. SIMM animations of the predicted motions revealed a "medial-thrust" gait pattern that drove the left knee inward, causing the ground reaction force vector to pass more laterally to the knee center than in the nominal experimental situation (Fig. 2). For the first set of cost function weights, the predicted adduction torque reductions were 32 and 34% in the first and second peaks, respectively, while for the second set, they were 54 and 56% (Fig. 3). The primary difference between the two sets of optimization results was that the second set predicted larger kinematic and kinetic changes to achieve the larger adduction torque reduction.

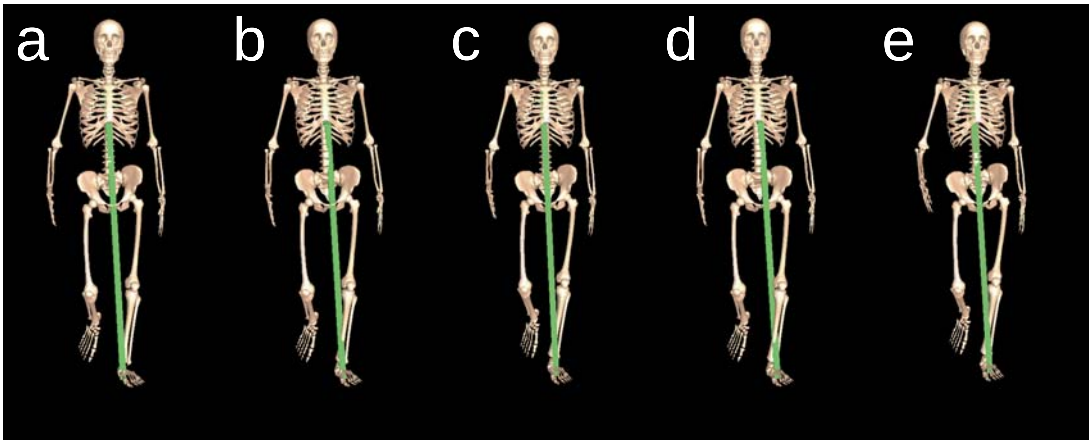

Figure 2: Visualization of moment arm of the ground reaction force vector about the knee center. a) Nominal experimental gait motion, b) Predicted gait motion with higher peak adduction torque, c) Experimental gait motion with higher peak adduction torque, d) Predicted gait motion with lower peak adduction torque, and e) Experimental gait motion with lower peak adduction torque.

After gait retraining, the patient was able to achieve external knee adduction torque reductions comparable to the optimization predictions (Figs. 2 and 3). When the patient attempted to walk using his old gait pattern, he produced adduction torque reductions of

35 and 32% in the first and second peak, respectively. When he walked using an exaggerated version of the predicted medial-thrust gait motion, the reductions were 50 and 55%.

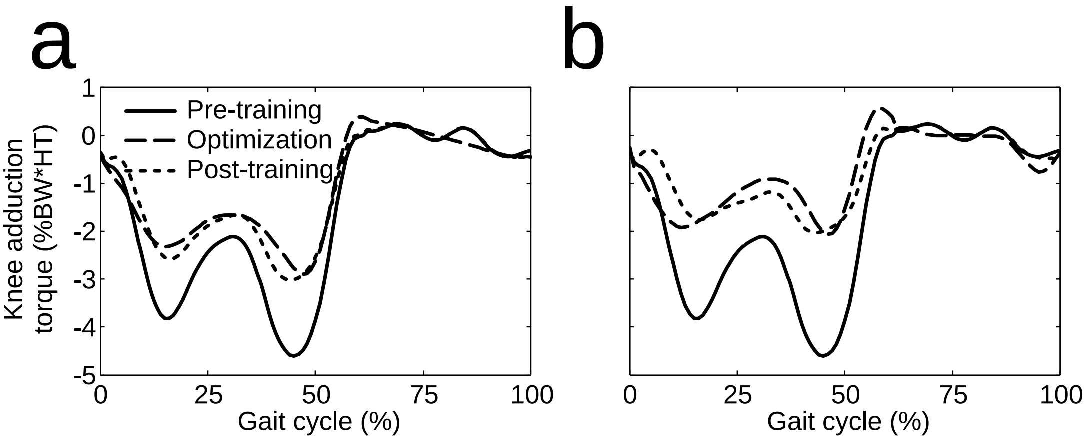

Figure 3: Left knee adduction torque measured experimentally for the nominal gait motion (solid lines), predicted by the optimizations (dashed lines), and measured experimentally after gait retraining (dotted lines). a) Higher peak adduction torque results. b) Lower peak adduction torque results.

5. DISCUSSION

This study used dynamic optimization of a patient-specific, full-body gait model to predict three-dimensional gait modifications that reduce both peaks of the external knee adduction torque curve simultaneously. Two optimizations were performed starting from the patient's nominal pre-treatment gait data – one with tighter and one with looser tracking of leg control torques and center of pressure. The predicted reductions of 32 to 54% in the first peak and 34 to 56% in the second peak were extremely close to the experimentally observed decreases of 35 to 50% and 32 to 55%, respectively, achieved by the patient after gait retraining. Furthermore, these decreases were comparable to the 30 to 50% observed following HTO surgery (Prodromos et al., 1985; Wada et al., 1998), which was the goal of the design process. The actual reductions achieved by the patient during normal walking would be somewhere within these ranges. To achieve these decreases, the optimizations predicted a "normal looking" gait motion that did not alter the foot path or trunk orientation. Instead, the optimizations medialized the knee by bringing it under the center of mass of the body while also shifting the center of pressure laterally under the foot. If generalizable to other patients with medial compartment knee OA, the predicted medial-thrust gait motion may provide a clinically useful rehabilitation strategy either apart from or in conjunction with HTO surgery (e.g., to reduce the chances of recurrent varus alignment).

Treating the knee as a simple pin joint was the most significant modeling assumption in our computational methodology. The direction of our best-fit pin joint axis accounted for the average values of knee adduction-abduction and internal-external rotation produced by the patient during gait. Given noise due to skin movement artifacts, it would be difficult to determine accurate limits on these secondary joint motions. Since the predicted adduction torque reductions were comparable to those observed experimentally, we do not believe that our pin joint knee assumption adversely affected our prediction process.

Another assumption in our computational methodology was that the selected cost function weights were representative of the patient's control strategy. Though we followed a systematic approach for selecting two sets of cost function weights, different weights will produce different optimization results. As in any engineering design study, the main goal is to achieve a final design that is better than the nominal one, whether or not the final design is the best one possible. Since the predicted gait modifications did, in fact, result in significant adduction torque reductions when implemented, this limitation is not a serious one.

The biggest limitation of our study was evaluation of only a single patient. Since the goal of the study was to assess the feasibility of using dynamic optimization of a patient-specific gait model to design a patient-specific treatment, we believe that use of a single patient was reasonable. If we were unable to demonstrate that the methodology works for at least one patient, there would be little motivation for studying a larger number of patients. Our next step will be to evaluate whether the same methodology will work for other patients with knee OA. These patients will have different nominal gait patterns, adduction torque peaks, varus malalignment, and lateral collateral ligament laxity, all of which may affect the effectiveness of our model-based approach.

6. ACKNOWLEDGMENTS

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