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Computational Assessment of Combinations of Gait Modifications for Knee Osteoarthritis Rehabilitation

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Abstract—Gait modification is a noninvasive strategy for reducing the external knee adduction torque in patients with medial compartment knee osteoarthritis. Recently, a novel "medial thrust" gait pattern characterized by knee medialization during stance phase has been shown to reduce both adduction torque peaks significantly. While changes in footpath (i.e., toe out angle and stance width) also affect the adduction torque peaks, the extent to which footpath changes may alter the effectiveness of medial thrust gait is unknown. This study used a validated patient-specific computational model to investigate this issue. A dynamic optimization framework that accurately predicted adduction torque changes caused by knee medialization or footpath alteration for a specific patient was modified to predict the simultaneous effect of both factors. Medial thrust gait optimizations were then performed for the same patient using imposed footpath alterations consisting of all possible combinations of three toe out angles (nominal $\pm 15°$) and three stance widths (nominal ± 50 mm). Overall, predicted adduction torque reductions produced by medial thrust gait were relatively insensitive to footpath alterations. The 32%–34% reduction in both peaks achieved with the nominal footpath was augmented by at most 9% and reduced by at most 3% for the altered footpaths. When combined with knee medialization, footpath alterations would likely have only a secondary effect on knee adduction torque reductions for this particular patient.

Index Terms—Biomechanics, dynamic optimization, knee adduction moment, osteoarthritis (OA).

I. INTRODUCTION

Osteoarthritis (OA) disables about 10% of the population above age 60 years and affects the knee more than any other joint [1]. Despite the growing burden of knee OA to society, researchers have made only limited progress at developing treatments that modify the course of the disease. One conservative treatment option with disease modifying potential is gait retraining. Researchers have investigated several gait modifications for reducing the external knee adduction torque, a surrogate measure for medial compartment load [2], [3], disease progression [4], [5], and pain [7]. These modifications include walking with decreased speed [7], decreased stride length [8], increased toe out angle [2], [9], increased stance width [10], and increased medial-lateral trunk sway [11].

While potentially therapeutic gait modifications are normally identified using a combination of intuition and experimentation, a "medial thrust" gait pattern involving knee medialization during stance phase was recently designed using a computational approach [12], [13]. This gait pattern appears normal to the naked eye, does not require changes to a patient's normal gait speed or stride length, and yet can reduce both knee adduction torque peaks by roughly the same extent as high tibial osteotomy surgery [13]–[15]. It is not known, however, whether changes in footpath (i.e., toe out angle and stance width) may be synergistic with knee medialization for reducing both knee adduction torque peaks further.

This study uses a computational approach to assess how footpath changes alter the effectiveness of medial thrust gait. The study is performed for a specific patient with medial compartment knee OA and uses a validated dynamic optimization framework [10], [13]. In addition to changes in the knee adduction torque, potentially detrimental or beneficial torque changes at neighboring joints are also predicted. The approach allows patient-specific assessment of combinations of gait modifications that may be synergistic with one another but difficult and time consuming to evaluate experimentally.

II. METHODS

A. Experimental Data Collection

Previously reported gait data collected from a patient with medial knee OA (male, age 37 years, height 170 cm, mass 69 kg, alignment 5° varus) were used for this study [13]. In brief, gait and isolated joint motion data were collected using a video-based motion analysis system (Motion Analysis Corporation, Santa Rosa, CA) and two force plates (AMTI, Watertown, MA). Institutional review board approval and informed consent were obtained. The patient walked at a self-selected speed of 1.4 m/s and one cycle (i.e., left heel strike to left heel strike) of gait data with no marker dropout was selected for use in the optimization studies. Since only the left leg had experimental ground reaction data for the entire cycle, optimization results are presented only for that leg.

B. Dynamic Model Development

A previously published dynamic, patient-specific gait model was used to predict medial thrust gait motions and loads starting from the patient's nominal gait data [13]. In brief, the full-body model is three-dimensional (3-D) and possesses 27 degrees of freedom (DoFs). The equations of motion were derived using the musculoskeletal modeling software SIMM with the dynamics pipeline (Motion Analysis Corporation, Santa Rosa, CA). Movement of the pelvis in the laboratory coordinate system was measured using three translational and three rotational DoFs, and the remaining 13 segments comprised four open chains branching from the pelvis with the following joint types: 3 DoF hips, 1 DoF knees (with constraint torques for knee adduction brought into evidence), 2 DoF ankles (nonintersecting axes), 3 DoF back, 2 DoF shoulders, and 1 DoF elbows. All joint and inertial parameter values were calibrated to the patient's nominal gait data and isolated joint motion data using previously published methods [10], [16].

For the subsequent predictive gait optimizations, the calibrated model was used to perform repeated inverse dynamic simulations. Inputs to the model were values of the 27 generalized coordinates, their first and second time derivatives, bilateral ground reaction forces and torques, and footpath alterations, while outputs were 29 joint loads (i.e., 27 loads associated with model DoFs, including six residual loads acting on the pelvis, plus two constraint torques for knee adduction), bilateral footpaths (not generalized coordinates), trunk orientation (also not generalized coordinates), and bilateral centers of pressure.

C. Optimization Problem Formulation

Nine predictive gait optimizations were performed to assess the simultaneous influence of knee medialization and footpath alteration on the patient's knee adduction torque peaks. Each optimization used a previously validated cost function that minimized the right and left knee adduction torque while tracking the patient's nominal leg control torques, centers of pressure, footpaths, trunk orientation, and pelvis residual loads (see [13] for details). Motion and ground reac-
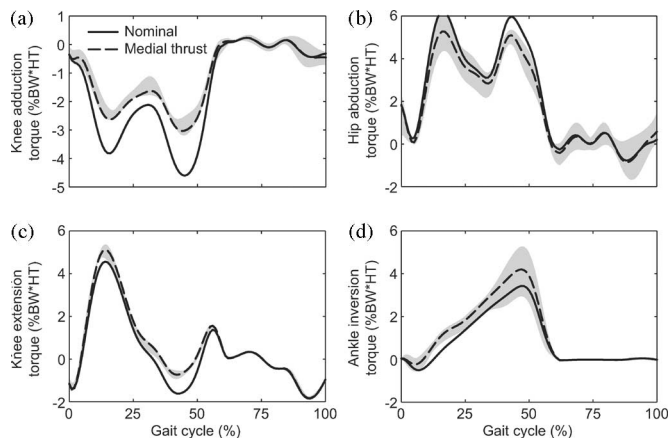

Fig. 1. Left knee adduction (a), hip abduction (b), knee extension (c), and ankle inversion (d). Torque curves measured for the patient's nominal gait motion (solid line) and predicted for the patient's medial thrust gait motion using the nominal footpath (dashed line). Shaded regions indicate range of predicted torque curves for medial thrust gait with nine footpath variations.

tion curves were parameterized using a cubic polynomial plus eight Fourier harmonics (i.e., 20 coefficients per curve), and the corresponding coefficients served as design variables. Motion curves for the shoulders, elbows, and pelvis horizontal translations were prescribed to match the patient's normal gait data. All optimizations used the Levenberg–Marquardt nonlinear least-squares algorithm in Matlab.

Different tracked footpaths were used for each of the nine gait optimizations. Footpaths for the right and left sides consisted of all possible combinations of three toe out angles (nominal ±15°) and three stance widths (nominal ±50 mm). The nominal toe out angle was approximately 7° on both sides, while the nominal stance width was approximately 40 mm as measured from the heel marker to the sagittal midplane of the body. Each footpath was created by adding two fixed offsets to the right and left nominal footpath measured in the laboratory coordinate system. An offset in internal-external rotation accounted for imposed changes in toe out angle, while an offset in medial-lateral translation accounted for imposed changes in stance width [10]. All optimization results are reported relative to previously validated medial thrust gait results for the nominal footpath [13].

III. RESULTS

Overall, footpath alterations had only a limited incremental influence on the 32% and 34% reduction in the first and second adduction torque peak, respectively, produced by medial thrust gait with the patient's nominal footpath [see Fig. 1(a)]. Changing the footpath decreased either peak by at most 9% and increased either one by at most 3% relative to the nominal footpath (see Table I, top section). Decreased toe out angle had the most favorable influence on the first peak (4%–8% additional reductions) but increased the second one (0%–3%). In contrast, increased toe out angle had the most favorable influence on the second peak (5%–9% additional reductions) while simultaneously decreasing the first one (0%–4%). Increased stance width had a generally favorable influence on both peaks (0%–9% additional reductions), while decreased stance width reduced the first peak only for toeing in (8%) and the second one only for toeing out (5%). The best combination for reducing the first and second peak simultaneously was an increased toe out angle with an increased stance width (4% and 9% additional reductions, respectively).

TABLE I
SUMMARY OF PREDICTED CHANGES IN TORQUE PEAKS RELATIVE TO MEDIAL
THRUST GAIT WITH THE NOMINAL FOOTPATH

	Stance Width Change (mm)	Additional Change in First Peak (%) Toe Out Angle Change (deg)			Additional Change in Second Peak (%) Toe Out Angle Change (deg)		
		+15	0	-15	+15	0	-15
Knee Adduction Torque	+50	-4.30	-2.01	-4.48	-9.11	-1.82	0.437
	0	-1.66	0	-5.25	-7.25	0	2.24
	-50	0.0269	0.386	-8.34	-4.56	1.57	3.48
Hip Abduction Torque	+50	-14.51	-7.69	1.96	-6.97	-2.14	0.823
	0	-8.12	0	10.2	-5.42	0	3.05
	-50	-1.57	7.50	16.8	-1.37	3.58	4.32
Knee Extension Torque	+50	0.978	1.21	-3.15	2.28	3.11	3.00
	0	3.22	0	-4.38	-0.895	0	-2.36
	-50	5.62	-0.982	-7.67	-5.29	-5.10	-6.93
Ankle Inversion Torque	+50	—	—	—	-36.4	-10.2	10.4
	0	—	—	—	-26.4	0	21.1
		—	—	—	-14.0	12.3	31.3

For the three leg control torques affected most by medial thrust gait (i.e., hip abduction, knee extension, and ankle inversion), changing the footpath significantly altered some peak values but not others [see Fig. 1(b)–(d) and Table I, bottom three sections]. Compared to the patient's nominal footpath, the altered footpaths changed the second hip abduction torque peak and both knee extension torque peaks by at most 8%. In contrast, footpath alterations produced additional changes in the first hip abduction torque peak of between +17% and –15% and in the ankle inversion torque peak of between +31% and –36%. Increased toe out angle with increased stance width was the most effective at lowering both hip abduction torque peaks (15% and 7%, respectively) and the ankle inversion torque peak (36%) but produced slight increases in both knee extension torque peaks.

IV. DISCUSSION

This study used a validated patient-specific computational model to assess how footpath changes affect knee adduction torque reductions produced by knee medialization during gait. Overall, footpath alterations had a relatively small influence (at most 9%) on the 32%–34% peak adduction torque reductions achieved by medial thrust gait with the patient's nominal footpath. However, footpath changes had a significant incremental affect on changes in some leg control torques. In particular, the first peak of the hip abduction torque curve was reduced by an additional 15% and the peak in the ankle inversion torque curve was reduced by 36% when toe out angle and stance width were increased together. This combination reduced the peak ankle inversion torque to below its nominal level while simultaneously reducing both knee adduction torque peaks by an extra 4%–9%. Thus, if ankle problems arise from clinical implementation of medial thrust gait, an increased toe out angle with increased stance width should be investigated as a possible solution.

The results of this study provide theoretical estimates for the knee adduction torque changes this particular patient is likely to achieve in clinical practice. These estimates likely capture the first-order effects that one would observe experimentally. The patient-specific model and computational framework used in our study have been validated experimentally for this particular patient using medial thrust gait [13] and footpath alterations [10] separately. Thus, it is reasonable to assume that predictions for combined knee medialization and footpath alteration will be reasonable as well. Our results suggest that additional gait retraining effort to alter the patient's footpath is not warranted, as the additional decrease in the critical first peak would be at most 4% assuming degradation in the second peak is unacceptable. Whether or not similar results would apply to other patients is currently un-known but can be investigated by following the same computational approach.

An effective training protocol for medial thrust gait needs to be developed before combinations of gait modifications can be investigated experimentally in a larger patient population. To date, three different laboratories have verified that medial thrust gait is effective for reducing the first knee adduction torque peak in particular [13]–[15]. Whereas [13] and [14] only used verbal instructions, [15] used a mirror to provide visual feedback and also investigated hip internal rotation rather than pelvis axial rotation to help medialize the knee. Until the most effective medial thrust gait training protocol is identified, investigation of simultaneous footpath alterations should probably be considered of secondary importance.

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