Short communication

Training multi-parameter gaits to reduce the knee adduction moment with data-driven models and haptic feedback ☆

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ABSTRACT

The purpose of this study was to evaluate gait retraining for reducing the knee adduction moment. Our primary objective was to determine whether subject-specific altered gaits aimed at reducing the knee adduction moment by 30% or more could be identified and adopted in a single session through haptic (touch) feedback training on multiple kinematic gait parameters. Nine healthy subjects performed gait retraining, in which data-driven models specific to each subject were determined through experimental trials and were used to train novel gaits involving a combination of kinematic changes to the tibia angle, foot progression and trunk sway angles. Wearable haptic devices were used on the back, knee and foot for real-time feedback. All subjects were able to adopt altered gaits requiring simultaneous changes to multiple kinematic parameters and reduced their knee adduction moments by 29–48%. Analysis of single parameter gait training showed that moving the knee medially by increasing tibia angle, increasing trunk sway and toeing in all reduced the first peak of the knee adduction moment with tibia angle changes having the most dramatic effect. These results suggest that individualized data-driven gait retraining may be a viable option for reducing the knee adduction moment as a treatment method for early-stage knee osteoarthritis patients with sufficient sensation, endurance and motor learning capabilities.

1. Introduction

At least 12% of U.S. adults over age 60 have symptomatic knee osteoarthritis (OA) (Dillon et al., 2006), and this percentage is growing due to an aging baby boomer generation, increased life expectancy and rising rates of obesity (Clarfield, 2002; Elders, 2000). Gait modification has been proposed as a method for lowering the knee adduction moment (KAM), a surrogate measure of medial compartment loading linked to the presence, severity, rate of progression and treatment outcome for medial compartment knee OA (Schnitzer et al., 1993; Baliunas, 2002; Sharma et al., 1998; Miyazaki et al., 2002; Wada et al., 1998; Hurwitz et al., 2002). Foot progression and lateral trunk angle modifications have been shown to influence the KAM (Guo et al., 2007; Lynn et al., 2008;

Mündermann et al., 2008). In one study a model-based subject-specific gait was determined using a variety of gait parameters (Fregly et al., 2007).

Real-time feedback is a promising strategy for gait modification training. Visual, audio, and tactile feedback have been implemented to alter knee loading (Barrios et al., 2010; Riskowski et al., 2009; Dowling et al., 2010). Wheeler et al. (in press) calculated the KAM in real-time, displayed this value through visual or tactile feedback, and allowed subjects to self-select gait modifications to reduce the KAM.

Most gait modification interventions tend to prescribe universal kinematic changes for all subjects. While this approach is straightforward to implement, large subject-to-subject variations (Chang et al., 2007; Mündermann et al., 2008) imply that for many subjects the intervention may be inadequate. In contrast, we propose an approach for predicting novel gaits based on data collected from experimental walking trials specific to each subject, hence 'data-driven'. Our primary objective was to determine whether data-driven gaits aimed at reducing the KAM by 30% or more could be identified and trained in a single training session. In addition, we sought to discover the association between the KAM and the tibia angle and compare it with modifications to foot progression and trunk sway angles.

2. Methods

2.1. Subjects

Nine healthy subjects (6 male, 3 female; age: 26.6 ± 4.1 yr; height: 175.6 ± 9.4 cm; mass: 67.5 ± 9.6 kg) participated after giving informed consent in accordance with Stanford University's Institutional Review Board. Nine subjects were sufficient for identifying a 30% KAM reduction based on a priori sample size calculations.

2.2. Baseline gait

An initial static trial was performed with markers on the following: calcaneus, head of second metatarsal, lateral/medial malleoli, lateral/medial femoral epicondyles, lateral mid-shaft shank, greater trochanter, lateral mid-shaft femur, left/right anterior superior iliac spines, left/right posterior superior iliac spines, left/right acromion and seventh cervical vertebrae. Medial malleolus and medial epicondyle markers were removed for walking trials.

Subjects walked normally at a self-selected speed on an instrumented treadmill (Bertec Inc., MA) for 2 min. Marker trajectories were recorded with an eight-camera Vicon system (OMG plc, Oxford, UK) at 60 Hz and ground reaction forces were recorded at 1200 Hz. Vicon data were streamed via TCP/IP to Matlab (Mathworks, Natick, MA) where kinematic parameter and KAM calculations were performed in real-time (Fig. 1A). Trunk sway was calculated from a line between markers on the left posterior superior iliac spine and the seventh cervical vertebrae intersecting with a vertical line in the frontal plane of the laboratory frame and took into account the offset, calculated the same way, found during the static trial. Tibia angle was determined from a line between markers on the lateral malleolus and lateral femoral epicondyle intersecting with a vertical line in the frontal plane of the laboratory frame. Foot progression angle was found from a line formed between markers on the calcaneus and second metatarsal and a line in the direction of progression. Knee joint center was the midpoint between the lateral and medial femoral epicondyles. The knee moment vector was the moment of the three-dimensional ground reaction force vector from the center of pressure about the knee joint center. The KAM was the component of the knee moment vector normal to the frontal plane of the laboratory frame. Tibia angles medial of vertical and toe in foot progression angles were considered positive. Trunk sway was the average of peak left and right trunk sway values over each cycle. Tibia and foot progression angles were averaged and the peak KAM value determined during the first 40% of stance for each gait cycle.

### 2.3. Single parameter gait retraining

Subjects next performed real-time gait retraining for single parameter kinematic modifications (Fig. 1C). The following trials were performed as deviations

from baseline: increase toe in 13–25°, increase toe out 13–25°, increase trunk sway 7–17° and increase tibia angle 5–13°. These modifications were chosen based on pilot trials and were intended to require significant but feasible changes to each parameter. Foot and tibia modifications were performed on the left leg. Each trial lasted 1–5 min and concluded once either the desired altered gait was demonstrated on 8 of 10 consecutive steps, or 5 min had passed. Treadmill speed and a metronome were used to enforce baseline walking speed and stride frequency to ensure decoupling of kinematic changes and speed of walking (Mündermann et al., 2004).

Haptic feedback was used to inform desired movements (Fig. 1B). Rotational skin stretch (Bark et al., 2010; Wheeler et al., 2010; Shull et al., 2010a) on the lower back indicated trunk sway changes, and C2 tactor vibration motors (EAI, Inc.) on the lateral aspect of the knee joint and lateral/medial foot informed tibia and foot progression angles, respectively. Smaller and larger amplitude skin stretch and vibration corresponded to smaller and larger error signals from desired movement changes, respectively. No feedback from a device indicated a correct value for that parameter on the corresponding gait cycle. For additional details on haptic feedback implementations see Shull et al. (2010b). Visual feedback was also used for some single parameter trials. A monitor in front of the subject displayed a stick figure with arrows indicating the desired movements for each gait parameter on each step. If the gait parameters were correct on a given step a green dot was displayed on the screen. Feedback was given during the last half of stance on each left foot step. Trial order and feedback types were randomized for all subjects. Both haptic and visual feedback was given to provide future insights into differences in learning rates and learning strategies. However, feedback type comparison and analysis was beyond the scope of this paper. The primary purpose of the single parameter trials was to determine the relationship between gait parameter changes and KAM changes and use these data for determining data-driven gaits.

2.4. Data-driven gait retraining

Lastly, subjects performed three trials of data-driven gait retraining (Fig. 1D). The protocol was identical as single parameter training with these exceptions: (1) all three gait parameter changes were trained simultaneously with real-time feedback, (2) only haptic feedback was used (no visual) and (3) final gait parameter changes were specific to each subject with the acceptable range being the target value plus 10° for foot progression angle, target plus 8° for trunk and target plus 5° for knee. Since pilot studies suggested (and results from this study confirmed) that increasing gait parameters beyond target amounts further reduced the KAM, and it was acceptable for final gaits to produce KAM reductions greater than but not less than 30%, the acceptable range for each gait parameter was the target value plus instead of target plus or minus. Before each trial, localized linearization, described fully in Shull et al. (2010b), was used to determine target gait parameter values for that trial. This method minimizes the
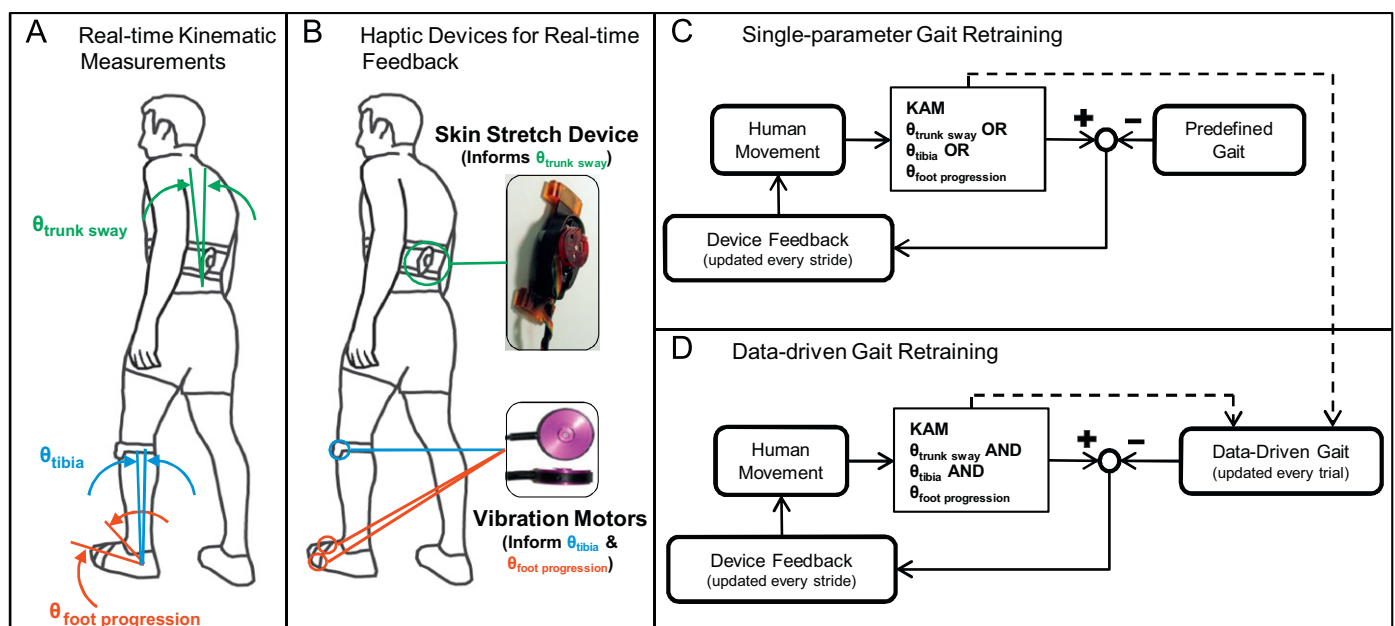
Fig. 1. (A and B) Real-time measurements and feedback. Haptic skin stretch device on the lower back applies rotational skin stretch via two contact points on the skin to inform lateral trunk sway adjustments. One vibration motor on the lateral knee joint and two motors on the foot inform lateral tibia angle and foot progression angle, respectively. (C and D) Flow charts for gait retraining. In single-parameter gait retraining, a single kinematic measurement is compared with the predefined desired gait parameter and device feedback is given based on the difference in values on each step. During data-driven gait retraining, all three gait parameters are trained simultaneously with device feedback based on the difference between desired kinematic parameters from the data-driven gait model, which is specific to each subject, and measured gait parameters. The data-driven gait model is updated after each single-parameter and data-driven gait trial with data collected during that trial.

overall gait change based on the relative influence of each parameter on the KAM determined from experimental data. For the first trial, correlations between kinematic parameters and the KAM were used in a weighted fashion, with higher correlations getting higher weights, to determine a new multi-parameter gait aimed at reducing the knee adduction by 20%. For the final two trials, a least squares fit between kinematic parameters and KAM values of each subject's previous single and multi-parameter trials was used to create a linear model centered on the previous multi-parameter gait. The model was used to project necessary kinematic changes to attain at least a 30% reduction in the KAM. The multi-parameter gait that produced KAM reductions nearest, but not less than, 30% was deemed each subject's altered, data-driven gait. Student t-tests were used to compare baseline and altered gait values.

3. Results

All subjects except one achieved the target KAM reduction of at least 30% (Fig. 2). All subjects responded to the haptic feedback devices by walking with the correct altered gait in 5 min or less. A typical example of baseline and data-driven altered gait is shown in Fig. 3. Data-driven gait patterns evidenced increases in tibia, foot progression and trunk sway angles and a decrease in KAM (Table 1, $p \leq 0.011$ for all variables). For baseline and single parameter trials, gait parameter changes generally varied linearly with KAM (Fig. 4) with the exception of tibia angles greater than ~5°, and scatter increased for increasing trunk sway values. Linear fits displayed slopes of 0.30, 0.042 and 0.026 for tibia, foot progression and trunk angles, respectively. Although the relationships between individual gait parameters and the KAM were linear for many regions, there was significant subject-to-subject variation as evidenced by differences in final data-driven gaits between subjects (Table 1).

4. Discussion

In this study data-driven gaits were identified and trained in a single session, producing KAM reductions of 29–48% and supporting the use of localized linear modeling for altered gait identification and real-time haptic feedback for training multiple simultaneous parameter changes. Although the direction of change for each gait parameter was generally consistent across subjects, the amount of change varied considerably. This was due to subject-specific differences in degree of influence of gait parameters on the KAM. The most striking example was trunk sway, where four subjects adopted data-driven gaits with changes of 0.5° or less while the remaining subjects evidenced modifications of 6.9° or greater (Table 1).
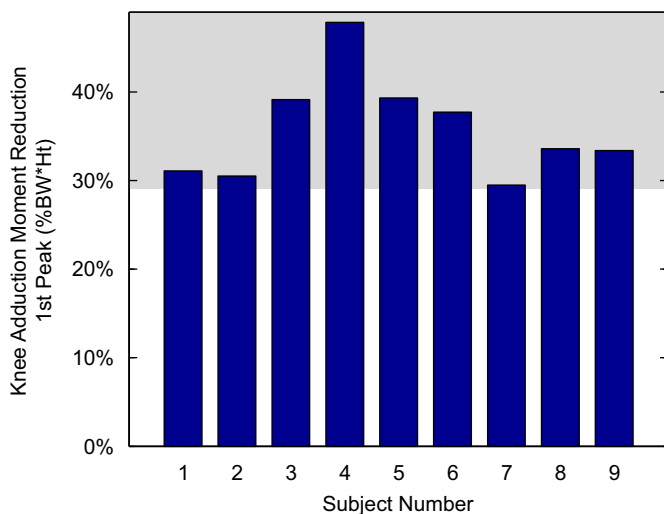

Fig. 2. Knee adduction moment response to data-driven gait training for individual subjects. The target reduction was 30% or greater.
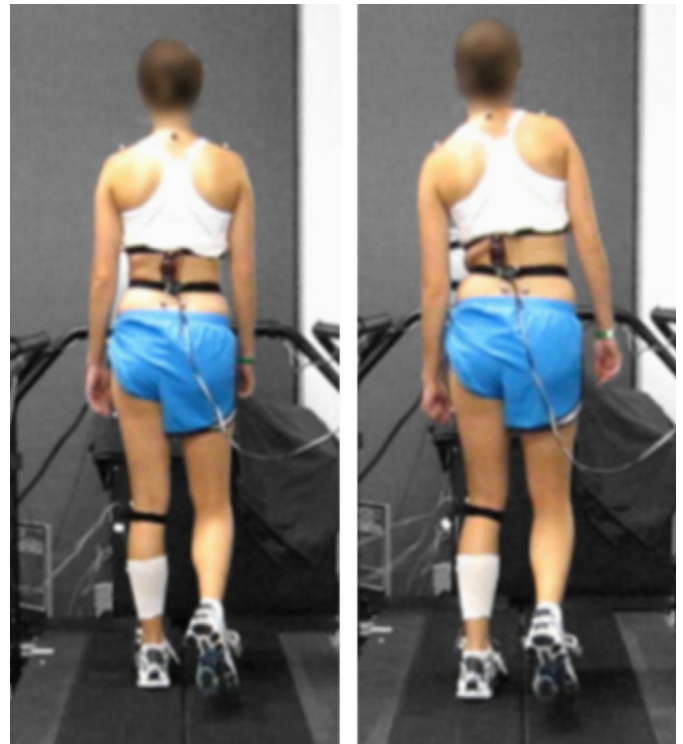

Fig. 3. Typical subject before and after data-driven gait retraining. (left) Baseline gait. (right) Altered gait with 5.4° increase in tibia angle, 10.2° increase in foot progression angle and 8.9° increase in trunk sway angle resulting in a 32% KAM reduction.

Tibia angle had a significant impact on the KAM (Fig. 4). Increasing the tibia angle moves the knee medially decreasing the knee adduction moment arm (Hunt et al., 2006) and produces a similar effect as 'medial thrust' (Fregly et al., 2007) or changes in knee adduction angle (Barrios et al., 2010). Additionally, toeing in and increasing trunk sway caused reductions in the first peak of the KAM, which aligns with the previous work (Lynn et al., 2008; Mündermann et al., 2008). The increasing scatter and relatively small influence of trunk sway on the KAM may be due to its timing-sensitive nature since relative phasing between trunk sway and KAM was not taken into account and only the overall peak value was used for feedback.

A limitation in this study was that training was performed on healthy subjects without knee OA. It is unclear whether multi-parameter real-time feedback will be equally effective for older subjects due to potential deficiencies in haptic sensation, proprioception, stability, endurance or learning abilities. Pain could also affect the success of gait retraining, though it has also been shown to be a strong motivator for adopting altered movement patterns (Henriksen et al., 2010; Shrader et al., 2004). The target population for future treatment is early stage knee OA patients with sufficient sensation, strength and motor control to perform such retraining trials, and previous gait retraining studies on knee OA patients give this task plausibility (Guo et al., 2007; Fregly et al., 2009). Additionally, the examination of potentially adverse secondary effects of gait retraining was beyond the scope of this paper. A recent study showed that a reduced KAM does not necessarily mean reduced medial compartment forces if the external flexion moment increases (Walter et al., 2010). Future gait training studies should consider this.

Our ability to rapidly adjust gait parameters to a desired effect illustrates a 'proof of concept' for future clinical applications using haptic feedback. Miniaturization of high-powered computing devices such as smart phones and development of accelerometer-based and other wearable measurement systems open

Table 1
Pre- and post-training gait mechanics for all subjects. Note the variation in kinematic changes highlighting the subject-specific nature of data-driven gait retraining. Bolded p-values denote 5% significance levels.

Subject	Tibia angle (deg.)			Foot progression angle (deg.)			Trunk sway angle (deg.)			Knee adduction moment (%BW Ht)		
	Baseline	Altered	Change	Baseline	Altered	Change	Baseline	Altered	Change	Baseline	Altered	Change
1	−4.9	1.1	6.0	−8.9	−0.4	8.5	2.5	12.6	10.1	4.5	3.1	−1.4
2	−4.6	0.6	5.2	−8.5	5.6	14.1	0.6	0.9	0.3	4.1	2.8	−1.3
3	−3.7	3.8	7.5	−9.5	7.3	16.8	1.8	9.4	7.6	3.7	2.2	−1.5
4	−2.0	5.7	7.7	−3.5	13.6	17.1	1.0	1.5	0.5	4.7	2.4	−2.3
5	−6.3	3.7	10.0	−12.7	5.2	17.9	1.6	8.6	7.0	6.1	3.7	−2.4
6	−4.1	4.3	8.4	−3.7	12.3	16.0	1.9	1.9	0.0	2.5	1.5	−1.0
7	−4.4	0.1	4.5	−2.8	5.4	8.2	2.1	1.2	−0.9	4.3	3.0	−1.3
8	−6.1	4.0	10.1	−1.6	17.8	19.4	1.1	8.0	6.9	3.5	2.3	−1.2
9	−2.2	3.2	5.4	−1.8	8.4	10.2	1.0	9.9	8.9	3.9	2.6	−1.3
ALL	−4.2 (1.5)	3.0 (1.9)	7.2 (2.1)	−5.9 (4.1)	8.4 (5.5)	14.2 (4.2)	1.5 (0.6)	6.0 (4.6)	4.5 (4.4)	4.1 (0.6)	2.7 (0.6)	−1.5 (0.5)
P−Value	$p < 0.001$			$p < 0.001$			$p = 0.011$			$p < 0.001$		
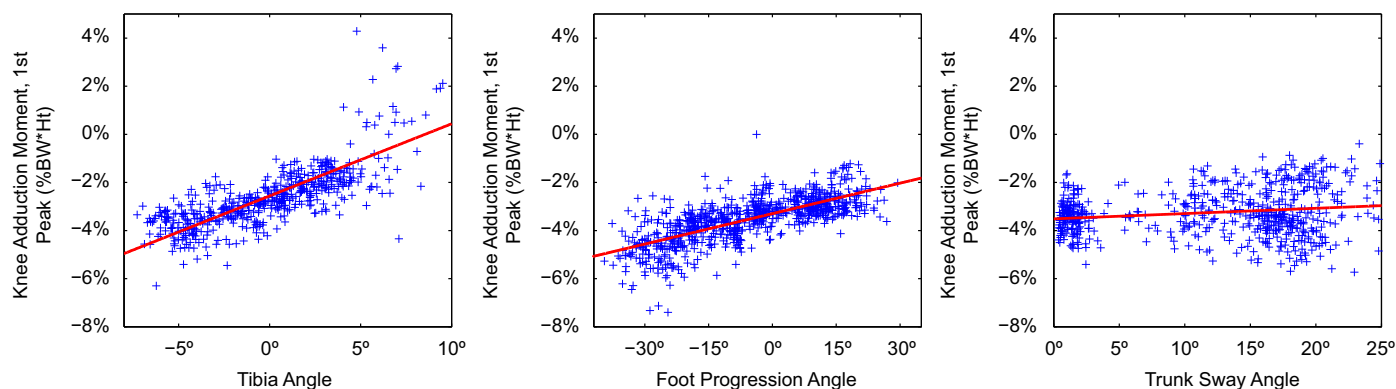
Fig. 4. Compiled data from all subjects for baseline and single-parameter gait change trials.

the door for a retraining system no longer confined to clinics or biomechanics laboratories. Instead with such a system, real-time feedback could be used to reinforce new gait patterns in any location with enough space to comfortably walk, paving the way for gait retraining as a preventative medical strategy.

In summary, this study showed that data-driven modeling with haptic feedback is an effective method for reducing the KAM. Significant reductions were evidenced in every individual due to the subject-specific nature of forming each model through experimental trials. Novel gaits were identified and adopted in a single training session. Future research should focus on knee OA patients and the development of a completely portable system.

Conflict of interest statement

None of the authors had any conflict of interest regarding this manuscript.

Acknowledgments

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