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Real-Time Knee Adduction Moment Feedback for Gait Retraining Through Visual and Tactile Displays

The external knee adduction moment (KAM) measured during gait is an indicator of tibiofemoral joint osteoarthritis progression and various strategies have been proposed to lower it. Gait retraining has been shown to be an effective, noninvasive approach for lowering the KAM. We present a new gait retraining approach in which the KAM is fed back to subjects in real-time during ambulation. A study was conducted in which 16 healthy subjects learned to alter gait patterns to lower the KAM through visual or tactile (vibration) feedback. Participants converged on a comfortable gait in just a few minutes by using the feedback to iterate on various kinematic modifications. All subjects adopted altered gait patterns with lower KAM compared with normal ambulation (average reduction of 20.7%). Tactile and visual feedback took longer to converge on an acceptable gait. This study shows that real-time feedback of the KAM can greatly increase the effectiveness and efficiency of subject-specific gait retraining compared with conventional methods. [DOI: 10.1115/1.4003621]

Keywords: gait retraining, osteoarthritis, knee adduction moment, real-time feedback

1 Introduction

Tibiofemoral joint osteoarthritis (TFOA) is a significant public health concern that affects millions of people. Progression of the disease is more common in the medial compartment of the knee (~77%), compared with the lateral compartment (~21%) or bilateral progression ($\sim 2\%$) [1]. Medial compartment TFOA is thought to have mechanical etiology, caused by nonuniform loading of the joint over time [2]. The knee adduction moment (KAM) during gait provides a surrogate estimate of the medial-lateral load distribution and has been associated with the onset, progression, and severity of medial compartment TFOA [3–5]. The KAM is the moment applied to the knee in the frontal plane and can be estimated during gait from the ground reaction force (GRF) vector, the center of pressure (COP) position, and the location of the knee joint center. These values can be measured in a gait analysis laboratory with force plates and a motion capture system. The KAM typically exhibits two peaks during the stance phase of walking, which correspond to the peaks in the vertical GRF [6]. Of these, the first peak has been shown to be higher in TFOA patients [7-9]and has been proposed to be the more important loading variable to reduce [10].

Severe cases of TFOA require total joint replacement, which is a costly and invasive procedure. In 2005, approximately 500,000 total knee arthroplasty surgeries were performed in the United States at a cost exceeding \$11 billion [11]. However, alternative clinical interventions may be used to slow the progression of the disease before joint replacement becomes necessary. The success of these interventions is often evaluated by comparing the KAM pre- and post-treatment. High tibial osteotomy (HTO) is a surgical intervention designed to reduce knee joint loads preventing or postponing the need for knee replacement [4,9]. This procedure involves the addition or removal of bone on the proximal tibia in an attempt to redistribute the medial-lateral loading on the joint. A good outcome of HTO is considered to be a 30–50% reduction in the peak KAM. It should be noted that patients who have largerthan-normal KAM prior to HTO surgery are also likely to maintain higher KAM postsurgery with poorer outcomes [4].

Orthoses, such as lateral heel wedges or knee braces, as well as gait retraining have shown promise as noninvasive interventions for altering gait. Lateral heel wedges shift the COP laterally and have shown modest reductions (less than 10%) in the peak KAM, significantly smaller than HTO [12,13]. Gait retraining strategies seek to alter the movement patterns to reduce the KAM. A few general strategies have been proposed, which include walking with the toes pointed outward, increasing trunk sway, taking shorter strides, walking slowly, hip adduction and internal rotation, and "medial-thrust gait." Toe out gait can reduce the second peak but does not impact the first peak significantly [2,9,14,15]. Increased trunk sway can reduce both peaks [16], but can be unnatural if the amount of trunk sway is large. Walking slowly may not be acceptable to some patients and as with any generalized modifications may not be effective for all patients. These modifications have all been shown to work well on average, but the large standard deviation in effectiveness means that there will be little to no change for many patients. Ideally, individualized gait modifications for reducing the KAM could be easily and quickly implemented for each subject. Fregly et al. [10] used subject-specific dynamic simulations to predict novel gaits that reduced the first peak of the KAM by 32–54% [10,17].

Several recent studies have shown that real-time feedback is effective for gait retraining. Barrios et al. [18] used visual real-time feedback of the knee adduction angle to retrain subjects to adopt modified gaits with significant KAM reductions (20%). Instrumented knee braces with auditory real-time feedback have been effectively used to reduce the rate of loading during heel strike [19,20], and tactile feedback in the shoe has been used to decrease lateral foot pressure during stance and reduce knee joint loads [21]. Shull et al. [22] utilized wearable haptic (touch) feed-

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back devices on the foot, lateral knee joint, and lower back to train simultaneous changes to foot progression, tibia, and trunk sway angles in real-time. Final modified gaits were subject specific producing KAM reductions of 29–48%.

The purpose of this paper is to present real-time feedback of the KAM as a method for gait modification to reduce knee joint loads. In this paradigm, subjects receive direct kinetic feedback, which contrasts the kinematic feedback provided in other studies. We detail an experiment in which subjects walked on a treadmill receiving real-time feedback of the first peak of the KAM via vision or vibration. Subjects iterated on gait modifications until a satisfactory gait was identified that produced a lower peak KAM. This approach used implicit feedback, which has proven effective for motor learning in other complex, repetitive tasks [23–25].

2 Methods

2.1 Subjects. Sixteen healthy subjects participated in the study (11 male, 5 female, mean age 29, range 21–49). Subjects were randomly selected to receive either vibration or visual feedback training with eight receiving vibration feedback and eight visual feedback. Approval was received from Stanford's Institutional Review Board, and all subjects gave informed consent prior to their participation.

2.2 Experimental Setup. The experiment was conducted in the Human Performance Laboratory at Stanford University. Motion capture data were collected with an eight-camera Vicon system (OMG plc, Oxford, UK). Reflective markers were used to reconstruct kinematic information. Three-marker clusters were placed on each of the subjects' feet, thigh, and shank consistent with a previously validated marker set [26]. Four markers were placed on both the pelvis (anterior and posterior superior iliac spines) and torso (acromion processes, seventh cervical spine, and sternal notch). Additional markers were placed on lower limb anatomical landmarks (medial and lateral femoral condyles and malleoli) but were removed after the static trial (with the exception of the left lateral femoral condyle marker). Since feedback was only given for the left leg, two additional markers were also placed on the left shank to provide redundancy in the marker set and improve tracking in real-time.

During testing, subjects walked on a split-belt, force-plate treadmill (Bertec Corp., Columbus, OH). Force and marker data were collected and synchronized with Vicon NEXUS software at frequencies of 1200 Hz and 60 Hz, respectively. Data were subsequently streamed via TCP/IP to MATLAB (Mathworks, Natick, MA) using Vicon's DataStream engine where knee joint moment calculations were performed in real-time. Visual feedback was given through a computer display in front of the treadmill and vibration feedback with a C2 Tactor (EAI Inc., Casselberry, FL) vibrotactile motor strapped with a Velcro band to the left forearm (Fig. 1). Visual feedback was generated in MATLAB and the vibrotactile motor was controlled with MATLAB's xPC real-time operating system. All data were captured and processed using a PC running WinXP (32 bits) with an Intex Xeon 3 GHz processor and an nVidia Quadro FX3450 256 Mbyte graphics card. See Ref. [27] for a detailed description of software interfacing between MATLAB and Vicon for real-time feedback.

The knee joint center was defined using the location of the left femoral condyle marker plus a frontal plane medial offset equal to half of the knee width. For all trials, the first peak KAM was computed in real-time as the maximum value of the cross product of the position vector from the knee joint center to the center of pressure and the ground reaction force in the frontal plane computed over the first 40% of stance. Stance time was determined from pretrial walking data. Data from prior studies have shown that the first peak KAM occurs before the 40% stance point (e.g., see Ref. [6]) and this was validated by examining post-trial data. Feedback was given during stance after the KAM calculation.



Fig. 1 Experimental setup. Reflective markers on the subject's segments enable motions to be tracked. Force plates in the treadmill gather force data. Feedback is provided with a vibration device or a visual display.

2.3 Gait Retraining. An initial static trial was captured while the subject stood stationary on the treadmill. Data from the static trial were used to build a model with labeled markers that were used for real-time calculations. Next, a calibration walking trial was performed. Each subject walked for 2–3 min on the treadmill at a self-selected speed to become comfortable with the device. Knee adduction moment values from the last 15 steps were averaged to determine the baseline KAM. All subsequent feedback calculations were relative to the baseline KAM.

Following the calibration trial, subjects performed gait retraining. The goal was to lower the KAM by reducing real-time KAM feedback signals during ambulation. Subjects were instructed to iterate on various gait modifications in an attempt to identify a new gait that produced a feedback signal that was as low as possible but was symmetric and sustainable. This meant that any modifications should be made on both legs, not resulting in unreasonably large increases in energy expenditure and not producing a gait that the subject would not consider using permanently. Biomechanical details of the study, such as KAM and medial compartment loading, were not described since most subjects were unfamiliar with these ideas. Instead, they were given the general description that reducing the feedback signal would reduce knee joint loading. To identify a new gait with a reduced KAM, we gave the following suggestions based on modifications from previous studies:

- walking with toes pointed in or out
- increased side-to-side trunk sway
- taking longer or shorter strides (while adjusting stride frequency to maintain the same speed)
- loading the inside or outside of the foot
- changing the distance between the feet (step width)

Subjects were instructed to try any one or combination of these and were free to make other modifications as well. After the subjects identified a satisfactory gait, they continued practicing for 1-2 min, and then 20 steps of altered gait data were collected and stored.

Visual feedback was displayed on a screen in front of the treadmill. A stair-step plot of the current step's first peak KAM, as well



Fig. 2 Sample of visual feedback display. The peak moment from the current step and the previous nine were displayed to the subject.

as the peaks from the previous nine steps, was shown (Fig. 2). The baseline moment was displayed as a dotted line for reference. In addition to providing a time history of data, the visual feedback allowed data to be conveyed with high spatial resolution. These properties of the feedback allowed users to detect trends in the KAM based on the modifications they made.

Because vibration feedback has a limited perceptual resolution [28], we binned the feedback into three levels that were easily distinguishable. This put a fundamental limitation on the resolution of the feedback but reduced ambiguity in remembering levels from previous steps. In all cases, a 0.5 s burst of vibration at 250 Hz was provided during the last half of stance. If the peak KAM on the current step was 80% of the baseline moment or larger, a large amplitude vibration was presented. If the peak KAM was 60–80% of the baseline, a low-amplitude vibration was provided, and no vibration was given for peak KAMs below 60%.

Once testing was complete, each subject was also asked to report what strategies they chose for the final gait and to rate the "awkwardness" of the new gait compared with their normal gait on a 0–10 scale (with 0 corresponding to no different and 10 being extremely awkward). The primary measures of interest from the study were the average first peak in the KAM (baseline and altered gait), the time required to complete the trial, and the awkwardness rating of the new gait.

To evaluate statistical differences in the results of the experiment, analyses of variance (ANOVAs) were performed. Repeated measures ANOVAs were performed to compare the results within subjects. When significant main effects were identified, paired t-tests were used to compare cases and when evaluating aggregate results and comparing the two types of feedback, a conventional ANOVA (between subjects) was performed with no pairing. Correlation coefficients were calculated to determine if the percent reduction in KAM was correlated with the awkwardness rating or the baseline KAM.

3 Results

All 16 subjects reduced their KAM for altered gaits compared with baseline. Figure 3 shows the KAM reduction, subjective awkwardness ratings, and feedback type for each subject. The magnitude of reduction in the KAM varied from as little as 3% to more than 50%. Significant main effects due to both subject and trial were identified. The average first peak of the KAM was significantly lower in the altered gait case (p<0.001). There was a weak correlation between the percent reduction values and the awkwardness rating (r=0.22). Similarly, there was a weak correlation between the percent reduction and the baseline KAM (r =0.38).

Average results for all subjects and results grouped by the feedback type are presented in Table 1. Percent reduction and awk-



Fig. 3 Percent reduction in the average value of the first peak knee adduction moment from baseline to altered gait trials along with the awkwardness rating for each subject. Error bars are 1 standard deviation of the mean (over ten steps).

wardness ratings for the visual and vibration feedback cases were not significantly different. However, the duration of the trial was significantly shorter with visual feedback compared with vibration (p < 0.01).

The most commonly reported modifications were toeing in (14 subjects), loading the inside of the foot (6 subjects), and increasing trunk sway (4 subjects). Other modifications varied between subjects and included some that were not suggested before the trial.

4 Discussion

This study showed that providing real-time feedback of the KAM and allowing subjects to self-select gait modifications was an effective gait retraining method for reducing the KAM. This real-time feedback approach for a repetitive task has the potential to greatly improve the speed of subject-specific gait retraining. The fact that vibration produced similar reductions in the KAM and awkwardness ratings compared with vision was somewhat surprising. The resolution of vibration feedback is much lower than vision and there is no time history other than the subject's memory. The similarity in performance between the two feedback methods may have been partly due to the fact that the subject only had coarse control over the KAM and so a relatively coarse feedback channel was still effective. However, the amount of time it took to converge on a new gait was longer with vibration than vision. This most likely occurred because subjects would only receive a change in vibration feedback if the peak KAM changed significantly (at least 20%). For visual feedback, trends of small changes could be detected and this information could be used for adjustment on each step. In future studies, it may be appropriate to first train subjects with visual feedback and then vibration could be used to maintain the adopted gait.

It is difficult to assess how "natural" the final adopted gaits were for each subject. While subjects were instructed to adopt a gait that was sustainable, there was subjectivity in how to interpret this. Some subjects adopted a gait that was considered more awkward than others. Despite this, there was not a strong correlation between percent reduction in the KAM and subjective awkwardness rating. Instead it seems that the KAM was very sensitive to small gait changes in some subjects and less sensitive in others. This could be a function of anatomy (e.g., varus/valgus align-

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Table 1 Average (standard deviation) results for all subjects grouped by feedback type. KAM is the average value of the first peak knee adduction moment. Moments are scaled by bodyweight×height. Awkwardness is a subjective rating between baseline and final altered gait with 0 being no different and 10 the most awkward. The final KAM was significantly lower than baseline in all cases (p < 0.01). No statistical difference was found between vibration and visual feedback with the exception of trial duration (p < 0.01).

	Baseline KAM	Final KAM	Percent reduction	Trial duration	Awkwardness rating
	(%BW Ht)	(%BW Ht)	(%)	(s)	(0–10)
All subjects	3.98 (0.90)	3.19 (0.93)	20.67 (15.46)	527 (252)	5.31 (2.27)
Visual	4.07 (0.89)	3.29 (0.98)	20.24 (15.94)	393 (113)	5.25 (1.98)
Vibration	3.90 (0.96)	3.09 (0.94)	21.11 (16.06)	661 (287)	5.38 (2.67)

ment), intersegmental interactions, or the nominal gait pattern of the person. How this variability might affect future studies with TFOA patients is unclear.

In observing the chosen gait modifications, there were some common trends. Toeing in was the most universally reported strategy. This is interesting as TFOA patients are often instructed to toe-out and aligns with previous literature showing that toeing out can reduce the second peak but not necessarily the first [2,9,14,15]. Another common strategy was loading the medial side of the foot. This likely moved the knee position medially through hip and ankle rotations [18], reducing the KAM moment arm, and produced a similar effect as training subjects to off-load the lateral side of the foot [21]. Trunk sway also proved to be an important self-selected gait pattern. Increased trunk sway changes the direction of the GRF, and thus can reduce the KAM moment arm. In contrast to other gait modifications, trunk sway is highly dependent on timing-the relative phasing between trunk angle and peak KAM. This timing component adds another element of difficulty and may explain why fewer subjects chose to adopt the strategy even though other studies have shown it to be highly effective [16].

One significant limitation of this study is that real-time training was performed on healthy young subjects without TFOA. It is unclear whether the strategies chosen to reduce the KAM in this study would be similar to strategies chosen by TFOA patients due to potential of increased pain, decreased learning ability, and motor control deficiencies from older age and physical impairments. Older patients may also have difficultly remembering gait modifications trained with real-time feedback, particularly if their selfselected gait was a complicated combination of movement alterations. To date, all real-time feedback training paradigms for reducing the KAM have been tested solely on healthy young subjects [18,21,22]; however, one study at least selected healthy young subjects with varus misalignment [18], a condition linked to higher baseline KAM and by extension higher risk of TFOA development. The subjects in this study were not screened for increased varus alignment or baseline KAM; thus, it is possible that they would never need to reduce the KAM and changes could actually have negative consequences. Additionally, we did not examine the potentially adverse secondary effects that these gait alterations could have. A recent study showed that a reduced KAM does not necessarily mean reduced medial compartment forces if the external flexion moment increases [29]. Future realtime feedback studies should consider this when training gaits, which reduce the KAM. Another limitation is that our focus was reducing the KAM in the frontal plane. The choice of coordinate frame for the KAM can be important, particularly for nonstandard gaits [30,31].

Gait retraining for this study was performed iteratively through repetitive cycles on an instrumented treadmill. While a previous study showed that specifically trained gait alterations learned during treadmill training translated to similar changes while walking overground [18], it is unclear whether this would hold true in the present study where subjects were free to self-select gait changes. A future approach could be to allow subjects to initially perform gait training on a treadmill with real-time feedback given on every step and then perform additional training overground with feedback administered less often. Additionally, since training took place in one of a relatively small number of biomechanics laboratories equipped with real-time visual and tactile devices, realtime processing software, 3D gait analysis, and an instrumented treadmill, widespread adoption of this technique may be limited.

One promising avenue may be to conduct the same real-time training with a system that is completely portable. In the current study, wearable tactile feedback, which is well-suited for portable implementation, was shown to be equally as effective as visual feedback. Additionally, the miniaturization of high-powered computing devices, such as smart phones and the increasing interest in accelerometer-based and other wearable human measurement systems, opens the door for a completely portable system that would not be confined to clinics or specialized biomechanics laboratories. Instead, with such a system, new gait patterns could be reinforced with real-time feedback by walking in a park, in a home, or anywhere with enough space paving the way for more widespread use of gait retraining as a preventative medical strategy.

This study demonstrated the feasibility of providing real-time feedback of the KAM for gait retraining. Tactile and visual feedback proved equally effective, although identifying altered gait patterns took longer for tactile feedback. Future studies should test patients with TFOA and examine long-term retention of adopted gait patterns.

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