Gait Retraining Outside the Lab

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ME 281: BIOMECHANICS OF MOVEMENT

WINTER 2023

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Abstract: Knee osteoarthritis (OA) affects over 600 million people worldwide and treatments range in invasiveness from requiring drugs to surgery. Pain caused by knee loading lowers the patient's activity level and quality of life. Gait retraining is a noninvasive technique to mitigate pain and change injurious movement patterns and is capable of reducing knee loads. OpenSim models demonstrated that it was possible to develop a muscle re-coordination strategy that lowers gastrocnemius (gastroc) activation without changing gait kinematics. Currently, however, gait retraining efforts require a heavily instrumented lab, limiting not only the ability to conduct therapy at a large scale but also the activities under which and duration that a patient can retrain for. This study examines strategies to retrain gait outside the lab. We expect to develop a wearable capable of measuring kinematics and muscle activations, observe reduced gastroc activations of 20% after a one hour retraining program, and verify that this leads to a reduction in knee loading. Furthermore we hope to enumerate strategies to reduce gastroc activation and validate OpenCap as a gait kinematics monitoring tool. Our results motivate novel therapies for pain reduction in Knee OA patients. More broadly, they suggest that gait retraining is viable at a large scale. The development and validation of these tools enables and encourages studies of other gait retraining techniques like knee-adduction-moment (KAM) and tibia load reduction.

INTRODUCTION

Movement is a key quality of life measurement and pathologies like osteoarthritis (OA) cause people to reduce movement because it becomes associated with pain *(Morris and Hardman, 1997; CDC, 1997)*. OA is a severe and common degenerative disease, with knee OA alone affecting 654.1 million people around the world (*Cui et al., 2020*). OA in the knee can occur in the patellofemoral joint, the tibiofemoral joint, or both (*Stefanik et al., 2016*). Patellofemoral OA (PFOA) is a specific case where worn and inflamed articular cartilage on the trochlear groove causes patients to report pain behind the knee cap *(Hoogervorst and Arendt, 2022),* while tibiofemoral OA (TFOA) is the degradation of cartilage between the tibia and femur. Knee pain is reported by 10-24% of OA patients over the age of 40, is more common in females, and is caused when the knee joint is loaded. There is no cure for knee OA other than knee arthroplasty, which is usually only considered at advanced stages of OA (*Cui et al., 2020)*. Therefore, recent research efforts have focused on developing early stage treatments, reducing pain, and slowing progression.

One of these areas of interest is gait retraining, which is a strategy that teaches people how to change certain parameters of their gait in order to reduce loading of the knee. Gait retraining for OA seeks to modify gait parameters like knee adduction moment (KAM), foot progression angle, trunk sway and/or gastrocnemius activation to reduce joint contact forces and thus reduce pain and slow progression *(Besier et al., 2011; Demircan 2020; Chen et al., 2017; Uhlrich et al., 2022a; van den Noort et al., 2015)*.

Many feedback modalities have been used to retrain gait and other movements, including visual, haptic, auditory feedback, and functional electrical stimulation. Kinematics are the most commonly used gait parameters in retraining strategies and tools for measurements include force sensors/plates, motion capture, inertial measurement units (IMU), and electromyography (EMG) data (*Van Gelder et al., 2018)*. Visual feedback is the most common mechanism of feedback and can enable the retraining of multiple parameters simultaneously, but we still don't know how to present visual feedback most effectively. For example, one study tested the effectiveness of four types (bar, polar plot, color change, graph) of visual feedback *(van den Noort et al., 2015)*. Furthermore, visual feedback is limited in scope by only being applicable on a treadmill in a lab.

Haptic feedback has been used to successfully adjust kinematics aimed at reducing knee loading *(Chen et al., 2017; Demircan, 2020)*. The location of the device on the body and details of vibration sequence all affect performance of these retraining methods (*Lurie et al., 2011*). In a 6 week study on people with OA, patients reduced first peak KAM with foot angle and experienced pain reduction *(Shull et al., 2013)*. Individualizing strategies for foot angle used haptics to improve on these results *(Uhlrich et al., 2018)*. Finally, haptics can retrain multiple gait parameters with a single device. Foot progression angle and step width, two parameters that influence KAM, were modified with a wearable ankle bracelet *(Chen et al., 2017)*.

The human body has more muscles than necessary to perform basic movements, which gives the nervous system the ability to optimize movements for specific tasks like efficient walking, safe climbing, or fast running. This extra muscular capacity is known as redundancy and allows the body to achieve task-specific performance goals. Accordingly, there exist multiple muscle coordination strategies for the same motion. Musculoskeletal simulations enable exploration of the relationship between neuromuscular control, kinematics, and metrics such as joint loading to identify favorable coordination strategies. Once an alternate muscle coordination is identified, feedback may be tested to investigate the feasibility of a particular gait modification.

The gastrocnemius is a biarticular muscle that crosses the ankle and knee joints. The soleus only crosses at the ankle, but these two muscles function to produce similar joint movements while walking. Since joint loading is affected by all muscles that cross the joint, the gastrocnemius contributes to knee loading while the soleus does not. Consequently, musculoskeletal simulations of walking in OpenSim (*Delp et al., 2007*) determined that lowering gastrocnemius activation, while increasing soleus activation can reduce knee contact forces while producing the same kinematics. Healthy subjects have been able to successfully learn this new muscle coordination strategy with visual feedback *(Uhlrich et al., 2022a)*. However, it remains unclear if a different wearable feedback mechanism will be effective in retraining gastrocnemius activation, enabling gait retraining to move outside of the lab and into someone's daily life.

Current efforts to investigate gait retraining and muscle coordination adjustments rely on complex biomechanics lab infrastructures *(Uhlrich et al. 2022a)*. Expensive, high-quality motion capture equipment and force plates are used to resolve gait kinematics, but these systems limit long term retraining and experiments outside of a controlled lab environment. The ability to conduct experiments outside of a lab would enable experiments that provide feedback for longer windows of time and attempt gait retraining during everyday activities. Additionally, larger and more diverse populations could be included.

In order to be able to conduct studies like this outside of the lab, a wearable device that can reliably deliver feedback to the user about their muscle activation is required. This device would need to collect position and EMG data, analyze it in real time, and provide the relevant feedback to the user. Devices like the neural sleeve by Cionic could be used but would need to be retrofitted with haptic actuators *(Robison et al., 2022)*. Using an off the shelf device like the neural sleeve is attractive because it saves time and has a team of people who will support experiments.

Prior research has shown that gait retraining can be used to reduce knee contact forces, which can alleviate pain and slow progression of osteoarthritis. A majority of current gait retraining methods focus on adjusting kinematic parameters (*Van Gelder et al., 2018*), however more recent work shows that a muscle re-coordination strategy can also be effective (*Uhlrich et al., 2022a*). All of these studies are severely limited by the ability to only conduct the retraining in a lab setting. Therefore, the goal of this study is to take the initial step towards gait retraining outside of the lab. To do this, we will develop and test a wearable device that delivers haptic feedback to the user to train them to walk with a reduction in gastrocnemius activation.

This experiment seeks to test 3 hypotheses. First, with the use of wearable feedback, individuals will be able to learn new muscle coordination strategies. Second, these coordination strategies will lower gastrocnemius activation. Third, lowering gastrocnemius activation will reduce knee loading. In addition to these direct hypotheses, we will also use this study to explore and categorize the strategies that people use to adapt their gait while attempting to learn how to change their gastrocnemius activation with haptic feedback. This will enable us to give suggestions of the most successful strategies to future participants. Additionally, we plan to validate OpenCap (*Uhlrich et al. 2022b*) on gait retraining in response to haptic feedback.

While this initial study will still be conducted in the lab, it addresses significant gaps in current gait retraining work and provides the necessary framework for gait retraining outside of the lab. Building from this study, future research will have the potential to enroll participants with OA, train with OpenCap outside of the lab, and investigate a longer timescale of training and retention.

PROPOSED RESEARCH

The proposed research study tests the hypotheses that wearable feedback facilitates learning of new muscle coordination strategies that lower gastrocnemius activation and knee loading. The study will serve as a preliminary investigation to justify performing similar investigations outside of the lab and with patients presenting for osteoarthritis. Accordingly, OpenCap will be validated as part of the preliminary investigation as it is a suitable approach to identifying gait kinematics in everyday environments.

Methods

Reduction in gastrocnemius activation will be statistically investigated by comparing the samples of gastrocnemius activations with and without haptic feedback. In order to distinguish two samples as statistically different with a power of 0.95 and type-1 error of 0.05 when such samples present a one standard deviation difference between their sample means, data will be collected for 10 subjects. Accordingly, subjects will be screened for prior injury and current pain.

Notwithstanding the goal of retraining gait in the everyday life of patients with osteoarthritis, the wearable haptic feedback device will be validated with healthy subjects in a controlled lab environment to build a foundation of preliminary data for future studies. Therefore, the equipment required for this study includes an instrumented treadmill, motion capture camera system, wireless EMG electrodes, and the wearable haptic feedback device. Motion capture will be used featuring markers on the anatomical landmarks detailed by the marker set in Table 1. Fourteen wireless Delsys EMG electrodes will be placed on the muscles described in Table 2. Finally, the wearable device will be adapted from the Cionic research kit (*Robison et al., 2022)*. Components of the device will include IMUs, EMGs, and haptic tactors. A preliminary wearable device as depicted in Table 3 will be finetuned following in lab validation to be compact and flexible for everyday use. Companies such as Nextiles and Strive demonstrate wearable technology that implement sewabale, conductive thread. Accordingly, the final wearable will implement sewable circuit components to enhance the comfort of the device. Two IMUs about the thigh and shank will enable step segmentation. The knowledge of the start and end of each stance phase will provide bounds for gastrocnemius and soleus EMG traces. A baseline gastroc activation will be established from a control walking trial before experimentation with gait modification. Then, the average of the envelope of each EMG trace will enable the identification of gastroc reduction from baseline for each step. Haptic feedback in the form of buzzes on the gastroc will inform a subject about the effect of their gait modifications throughout experimentation.

Table 1. Marker set using anatomical markers identified by bony prominences and reference frames in areas that are not occluded by walking

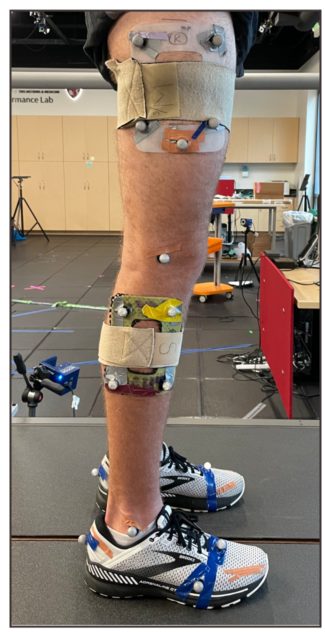
<table>
<tr><th colspan="2">Motion Capture Markerset</th><td rowspan="6"></td></tr>
<tr><td>Foot</td><td>2nd and 5th metatarsal, calcaneus</td></tr>
<tr><td>Ankle</td><td>Lateral and medial malleolus</td></tr>
<tr><td>Hips</td><td>Anterior superior iliac spine (ASIS),
Posterior superior iliac spine (PSIS)</td></tr>
<tr><td>Shoulders</td><td>AC joint, C7 vertebrae, sternum</td></tr>
<tr><td>Reference Frame Plates</td><td>Shank and thigh</td></tr>
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Table 2. Electromyography layout to support post-processing optimization for device validation

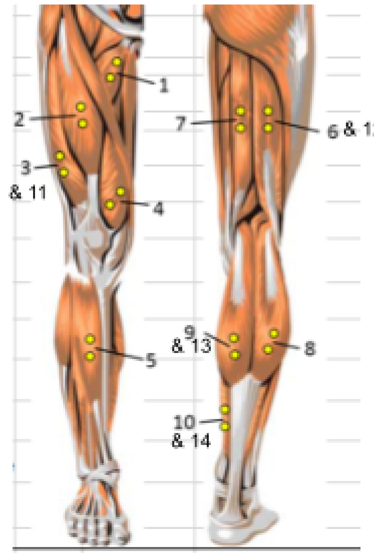
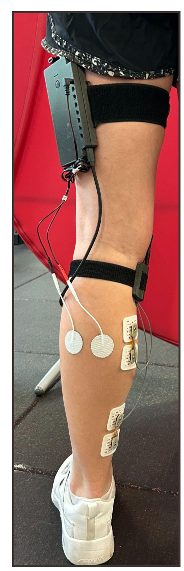
EMG Placement		
1) Adductor [ADD]	8) Lateral Gastroc [LG]	
2) Rectus Femoris [RF]	9) Medial Gastroc [MG]	
3) Vastus Lateralis [VL]	10) Soleus [SOL]	
4) Vastus Medialis [VM]	11) Vas Lat Contralateral [VL_cont]	
5) Tibialis Anterior [TA]	12) Lat Hams Contralateral [BF_cont]	
6) Lateral Hams [BF]	13) Medial Gastroc Contralateral [MG_cont]	
7) Medial Hams [ST]	14) Soleus Contralateral [SOL_cont]	

Table 3. Wearable device to apply appropriate haptic feedback for gait retraining

Wearable Device		
IMUs	Embedded within 3D printed enclosures about the thigh and shank	
EMGs	Externally attached with gel electrodes	
Haptic Tactors	Externally attached to the gastrocnemius	

Each subject will perform a single testing session at the Stanford Human Performance Lab. Before the subject arrives, the HPL will be prepared by calibrating the motion capture system, setting up OpenCap, turning on the Bertec treadmill, and pairing the Delsys EMGs. After obtaining consent, the subject will be prepped by attaching the 14 EMG sensors with tape to the muscles as depicted in Table 3 and will warm up with a three minute jog. Four maximum activation tests using isokinetic and isometric movements will enable normalization of the tibialis anterior (TA), biceps femoris (BF), adductors, and rectus femoris (RF) EMG channels in Cortex respectively. Five maximum activation jump trials will be performed to collect maximum activation values for normalization of the other muscles included in the EMG data collection. The wearable haptic device and reflective motion capture markers will then be placed on the subject. A static motion capture trial will be collected for calculation of anatomical reference frames from tracking reference frames during post processing. Capture of RGB photos of the subject during the static trial will allow marker replacement should a marker come off during testing. A short walking trial will also be conducted to allow the subject to experience the sensation of the treadmill and to collect dynamic motion capture data. The static and dynamic marker sets will then be labeled in Cortex. Then, there will be a 1 minute baseline trial, in which the participant will walk naturally and at the end of this minute an average gastrocnemius activation value will be calculated. This value is referred to as "baseline" and each value of gastrocnemius activation during the remaining trials will be compared to it to evaluate the percent change.

Three, six-minute walking trials will provide a subject the opportunity to experiment with gait modifications to attempt to achieve no haptic feedback, thus indicating they reached the goal gastrocnemius activation reduction from baseline. Specifically, the scheme of haptic feedback is as follows: two sequential buzzes will indicate gastroc reduction for the most recent step was less than ⅓ of the goal, one buzz will indicate a reduction greater than ⅓ of the goal but less than the goal, and an absence of buzzes will indicate gastroc reduction reached or exceeded the goal.

Each six-minute trial will start with four minutes of exploration with feedback. During this time, participants will be encouraged to experiment with different strategies of walking, while paying attention to what they adjust and how the corresponding feedback responds. In the fifth minute, the subject will be asked to converge on what they perceived as the optimal strategy while receiving feedback. The haptic feedback will be removed in the sixth minute, and the subject will attempt to continue performing their converged gait modification. The optimal gastrocnemius activation reduction in trial 1 is 30%. Based on previous research (*Uhlrich et al., 2022a*), this is an ambitious goal, but can be achieved and was chosen to encourage people to make the greatest reductions possible. Understanding that individual people have different capacities to change their muscle coordination, the goal will be individualized based on performance. In the following two trials, the goal will be dynamically scaled from 30% to 5% greater than the max reduction performed in the previous trial. For example, if a participant was able to reach 15% reductions from baseline, their new goal will be set to 20%. To record the strategies used, subjects will be asked to answer the following questions after each trial: "What strategies did you try during the four exploration minutes in this trial? What strategy did you converge on during the final minute?"

After having time to test many strategies for reducing gastrocnemius activation, participants will then practice their optimal gait modification strategy with feedback for ten minutes. Then the subject will take a ten minute break. The final trial is a six minute retention trial where a subject will walk with their best overall gait modification strategy without feedback. An end of session interview will be conducted to ask the following questions: "What strategy did you find most effective for the last minute of feedback training and retention? What were you thinking about to retain the optimal strategy when feedback was removed? Do you think you would be able to implement this strategy into your daily life?"

Following data collection, motion capture tracking data would be processed. Subsequently, a series of MATLAB scripts will be fine tuned to prepare the motion capture data to be able to scale an OpenSim model to the data. Analysis of the EMG data across the trials will test hypothesis one, that individuals can learn a muscle coordination strategy with wearable haptic feedback, and two, that the strategy will reduce gastrocnemius activation. Inverse kinematic, inverse dynamics, and optimization will be calculated to quantify the knee loading during the retraining testing protocol and test hypothesis three, that the strategies used to decrease gastrocnemius activation do reduce knee contact forces.

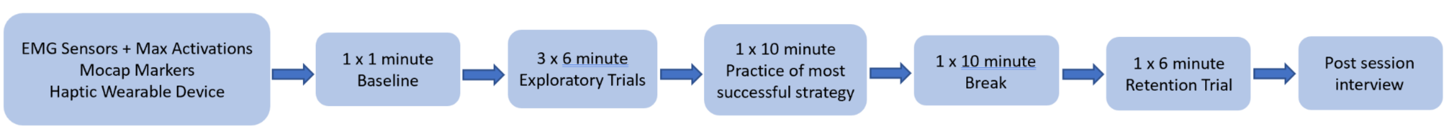


Figure 1: Summary of Experimental Methods

<u>Expected Results</u>

We anticipate that subjects will exhibit a decrease in gastrocnemius activation and that the magnitude of the change will increase with the number of trials performed. Furthermore we expect that in the retention phase, there will be an increase relative to the feedback phase but a reduction relative to the baseline. Recently, we were able to collect some pilot data following the protocol detailed here. Figure 2 shows the percent change of gastrocnemius activation from baseline for each trial: baseline, intervals with and without feedback for each exploratory trial, and the retention trial. There is an average reduction between 12 and 30% from baseline, which provides a positive indication for the results of our study.

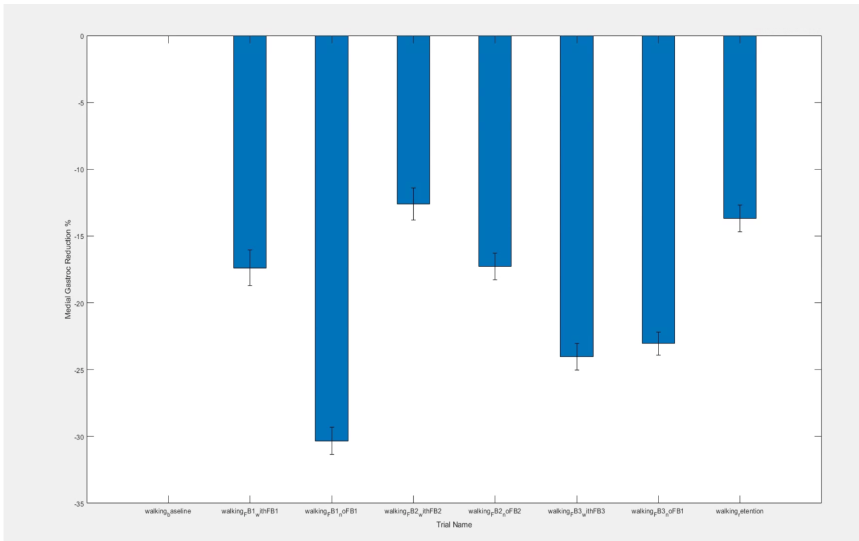


Figure 2: Pilot Data for Gastroc Reduction across Multiple Walking Trials

In the final 6 minute retention phase, we expect to see a regression towards the baseline as illustrated in Figure 3. Overall, however, we expect the retention to still be an improvement from the baseline. It will also be important to look at the retention of each trial individually to identify which trial the most successful strategy emerged from.

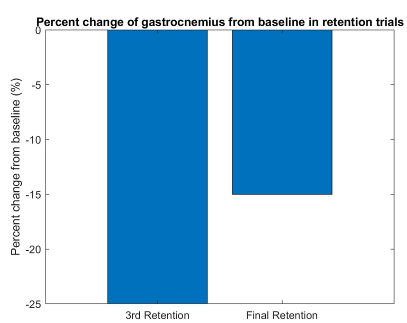


Figure 3: Artificial Expected Data for Gastroc Reduction Retention

One component of the study is enumerating strategies that subjects use to reduce their activation and pairing them with an average activation change. For each subject, we plan to collect strategy annotations after each exploratory phase and after the 10 minute single strategy phase. While each subject will have four opportunities for feedback, we anticipate most will use one of the strategies from the trail in their single strategy phase. We expect some participants to propose strategies that change gait kinematics and we will include these strategies even though the aim is to identify strategies that leave kinematics constant. Table 4 exemplifies strategies and corresponding descriptive statistics that may result from aggregating post-trial interview responses with respect to optimal gait modification strategy.

Table 4. Wearable device to apply appropriate haptic feedback for gait retraining

Strategy	**Frequency used (% participants)**	**Average % gastroc change**
Relax knee during stride	50	-18
Lean back	75	-15
Crouch	40	-21

In addition to the example results presented here, we would compare joint angles of the hip, knee, and ankle during normal walking and with the gastrocnemius avoidance strategy. We would also compare EMG values for muscles other than the gastroc, especially muscles that also cross the knee like the quadriceps, to verify that the gait retraining did not cause an increase in activation of another muscle that would counteract the desired decrease in knee loading.

<u>Experiment Timetable and Limitations:</u>

The expected duration of the study would be ten weeks assuming minimal modification of the base Cionic research kit. Recruiting subjects and conducting data collection would occur in parallel with data processing and analysis. The proposed study attempts to validate the use of a wearable haptic feedback device to reduce gastroc activation and knee loading during gait. The study, however, investigates each subject during a single session in a lab as opposed to multiple days and sessions. Additional studies should investigate multi-day retention of gait retraining strategies.

CONCLUSION

The ability to change both muscular and kinematic gait parameters can have a significant impact on reducing knee loading and thus pain and progression of knee osteoarthritis. Gait retraining through kinematics has been widely studied but coordination of muscle activation is a new target. Lowering gastrocnemius activation reduces knee loading and could provide a treatment or pain relief option to people with OA. Previous research relied on visual feedback for gait retraining, limiting the training to a lab setting and restricting the impact this could have on someone's everyday life. Therefore, the study proposed here is novel and important because it is the first essential step towards conducting gait retraining studies outside of the lab. By creating and testing a wearable haptic feedback device, validating OpenCap for gait retraining, and gathering more insight into strategies to recommend, we can eliminate the constraint of a lab in gait retraining treatment and pave the way for future studies. After completing this study, the strategy can be moved to out of lab training, as well as tested in an OA population to evaluate reductions in knee loading and associated pain.

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