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Foot center of pressure manipulation and gait therapy influence lower limb muscle activation in patients with osteoarthritis of the knee

Yulia Goryachev [a,*], Eytan M. Debbi [a], Amir Haim [a,b], Nimrod Rozen [c], Alon Wolf [a]

[a] Biorobotics and Biomechanics Lab, Faculty of Mechanical Engineering, Technion-Israel Institute of Technology, Haifa, Israel
[b] Department of Orthopedic Surgery, Sourasky Medical Center, Tel Aviv, Israel
[c] Department of Orthopedic Surgery, Ha'Emek Medical Center, Afula, Israel

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ABSTRACT

Background: Foot center of pressure (COP) manipulation has been associated with improved gait patterns. The purpose of this study was to determine lower limb muscle activation changes in knee osteoarthritis patients, both immediately after COP manipulation and when COP manipulation was combined with continuous gait therapy (AposTherapy).

Methods: Fourteen females with medial compartment knee osteoarthritis underwent EMG analyzes of key muscles of the leg. In the initial stage, trials were carried out at four COP positions. Following this, gait therapy was initiated for 3 months. The barefoot EMG was compared before and after therapy.

Results: The average EMG varied significantly with COP in at least one phase of stance in all examined muscles of the less symptomatic leg and in three muscles of the more symptomatic leg. After training, a significant increase in average EMG was observed in most muscles. Most muscles of the less symptomatic leg showed significantly increased peak EMG. Activity duration was shorter for all muscles of the less symptomatic leg (significant in the lateral gastrocnemius) and three muscles of the more symptomatic leg (significant in the biceps femoris). These results were associated with reduced pain, increased function and improved spatiotemporal parameters.

Conclusions: COP manipulation influences the muscle activation patterns of the leg in patients with knee osteoarthritis. When combined with a therapy program, muscle activity increases and activity duration decreases.

1. Introduction

Osteoarthritis (OA) is the most prevalent form of arthritis and occurs most commonly in the knee joint (Hogenmiller and Lozada, 2006). OA of the knee is one of the most common causes of disability in the elderly, affecting over 21 million people in the United States alone (Dillon et al., 2006; Felson et al., 1997). Patients with OA of the knee usually complain of pain, stiffness, poor function and muscle weakness (Hogenmiller and Lozada, 2006). Indeed, studies have shown that the muscle activity in the lower limb of patients with knee OA is below normal (Childs et al., 2004; Mc Alindon et al., 1993). Additionally, researchers have found that patients with knee OA have a longer duration of muscle contraction in comparison to healthy controls (Childs et al., 2004; von Tscharner and Valderrabano, 2010).

Several studies have shown that muscle activity in knee OA can be improved through strength training, neuromuscular stimulation and standard rehabilitation exercises (Suetta et al., 2004; Graham and Fisher, 2003; Tal-Akabi et al., 2007). Other studies have shown that agility and perturbation training can improve the gait patterns of patients with knee OA (Elbaz et al., 2010; Fitzgerald et al., 2002; Hurley, 2003). Laterally wedged foot orthoses have been used for many years to treat medial compartment knee OA, which is the most common type of knee OA (Graham and Fisher, 2003). These orthoses have been shown to improve the pathological kinetics and kinematics in knee OA (Kerrigan et al., 2002). Previous studies have suggested that these orthoses act by shifting the center of pressure (COP) in the foot, leading to a reduction in the moment arm of the knee adduction moment (KAM) and thus the KAM itself (Maly et al., 2002).

In two previous studies, Haim et al. (2008, 2010) introduced a unique biomechanical device that is thought to combine COP shifts with agility and perturbation training. This device is a foot-worn platform with two adjustable convex rubber elements attached to its base. Through adjustment of the elements, the device is

* Corresponding author. Address: Faculty of Mechanical Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel. Tel.: +972 4 8295945.

E-mail addresses: ygenis@gmail.com, yuliag@techunix.technion.ac.il (Y. Goryachev).

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capable of changing the patient's COP during walking. In addition, the convex design of the two elements causes a reduction in the base of support of the patient thereby creating minor perturbations during walking that may challenge the neuromuscular control (AposTherapy). These authors (Haim et al., 2008, 2010; Goryachev et al., 2011) showed that the device influences the kinetics, kinematics and muscle activation in the lower extremity of healthy individuals. For example, a significant correlation between the magnitude of the KAM and the coronal orientation of the COP was found in these individuals (Haim et al., 2008). In addition, significant changes in the EMG activity of the distal muscles of the lower limb were observed in response to coronal and sagittal COP manipulations (Goryachev et al., 2011).

Several studies have examined the influence of prolonged therapy with this device in knee OA patients (Elbaz et al., 2010; Bar-Ziv et al., 2010). These researchers (Elbaz et al., 2010; Bar-Ziv et al., 2010) have found that such a therapy program was able to significantly improve the spatiotemporal gait parameters, pain, function and quality of life of the patients, as assessed by means of the self-reported Western Ontario and McMaster Osteoarthritis Index (WOMAC, Roos et al., 1999). However, the influence of the intervention on objective gait metrics has not yet been determined.

Our institute has a complex research project (No. NCT00724139) to analyze the effect of AposTherapy on different biomechanical parameters of subjects with knee OA. The purpose of the project is twofold. First, the project aims to determine how specific changes in foot COP directly and immediately influence kinetics, kinematics and muscle activation in the lower limb. Second, the project aims to determine how a prolonged therapy program, with patient-specific calibration of the device, influences barefoot kinetics, kinematics and muscle activation in the lower limbs of these patients. Haim et al. (2011) summarized the direct influence of COP shifts induced by the biomechanical device on the kinetic and kinematic gait parameters. They found that modulation of the COP coronal trajectory from medial to lateral offset resulted in a significant reduction of the KAM, similarly to the healthy population study (Haim et al., 2008).

In the present study we analyzed the changes in muscle activity during gait of these patients. This report provides both the results of the immediate influence of COP manipulation and the effect of 3 month training therapy. Specifically, since patients with knee OA have been shown to have lower muscle activity and longer duration of muscle contraction compared to healthy individuals (Childs et al., 2004; Rasch et al., 2007; von Tscharner and Valderrabano, 2010), the study aimed to determine if the therapy program could return some of these changes toward normal. Self-reported measurements (WOMAC), and spatiotemporal gait parameters (gait velocity, cadence and step length) were taken to validate our results.

The study was designed to test the hypothesis that COP modifications in the coronal plane will immediately and significantly alter the activity of medial and lateral muscles of the lower limb and that, following training, muscle activity in each muscle will increase while the duration of muscle activity will decrease.

2. Methods

2.1. Participants

The study cohort was comprised of 14 female patients with equivalent shoe sizes and similar anthropometric profiles. The patients' mean ± SD age was 59.9 ± 6.2 years, height was 160.7 ± 6.3 cm and weight was 77.4 ± 8.9 kg. Inclusion criteria were symptomatic bilateral medial compartment knee OA for at least 6 months, fulfillment of the American College of Rheumatology (ACR) criteria for OA of the knee (Altman et al., 1986) and radiographic signs of OA in the medial compartment of the knee of grade two or greater on the Kellgren & Lawrence (K&L) scale (Kellgren and Lawrence, 1957). Exclusion criteria included any other orthopedic musculoskeletal or neurological pathology, prior knee surgery (excluding arthroscopies), significant co-morbidities affecting the back, hip or foot, other major systemic diseases and an inability to ambulate without the use of a walking aid. Subjects were recruited from the Department of Orthopedics, Ha'Emek Medical Center, in Afula, Israel. Approval from the Ethics Sub-Committee was obtained. The study was registered in the NIH clinical trial registration system (No. NCT00724139). The purpose and methods of the study were explained to the subjects and all participants gave written informed consent prior to the study.

2.2. The biomechanical system

The biomechanical device (APOS System, APOS–Medical and Sports Technologies Ltd., Herzliya, Israel) utilized in the study has been described previously (Haim et al., 2008). The device consists of two convex-shaped biomechanical elements attached to each foot using a platform in the form of a shoe (Fig. 1). The elements can be adjusted to specific settings that induce specific COP patterns in the foot during gait. The devices used in the study were generously donated by the manufacturer prior to the study.

2.3. Experimental protocol

2.3.1. COP manipulation

All subjects enrolled in the study were instructed to refrain from using any analgesic medication for a 2-week washout period prior to the study. In the first part of this study, the biomechanical device was calibrated to several COP settings for each patient to determine the immediate effects of each COP setting on the muscle activity in the lower limb. A single trained physiotherapist performed each calibration. The first setting was the "functional neutral sagittal axis", defined as the position in which the apparatus conveyed the least valgus or varus torque at the ankle in that specific individual (Fig. 1b). The device was also worn without any elements (control configuration; Fig. 1c), lateral sagittal axis (both elements moved 1.2 cm laterally from the neutral sagittal axis; Fig. 1d) and at a medial sagittal axis (both elements moved 0.8 cm medially from the neutral sagittal axis; Fig. 1e). A pilot trial conducted to assess the stability of the apparatus determined that satisfactory walking stability for healthy adults can be maintained within the range of 1.5 cm medial and 2 cm lateral deviation of the biomechanical elements from the neutral sagittal axis (Haim et al., 2008). Muscle activation was measured at each COP configuration. The configurations were tested in a random order on the same day.

2.3.2. Therapy program

In the second part of the study the biomechanical device was used as part of a therapy program (AposTherapy, Elbaz et al., 2010) for the same patients to determine the muscle activation changes in barefoot walking after the treatment. At the beginning of the training program the device was appropriately calibrated to each patient by a trained physiotherapist, and the patients were instructed to follow a treatment protocol similar to that reported by Elbaz et al. (2010). In brief, this protocol includes walking with the device on a daily basis in gradually increasing periods of time, until 30 min of walking per day is reached. Muscle activation testing was carried out during barefoot walking at baseline and after 3 months of therapy.

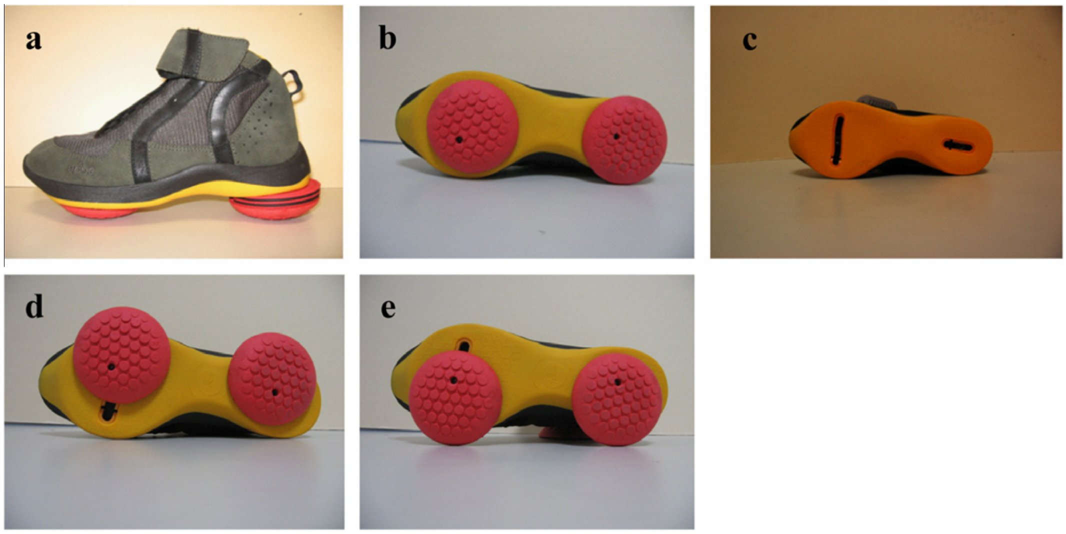

Fig. 1. The biomechanical platform set at several COP configurations. (a and b) Functional neutral sagittal axis configuration, defined as the position in which the apparatus conveyed the least valgus or varus torque at the ankle in that specific individual. (c) Device without any elements (control configuration). (d) Lateral sagittal axis configuration. (e) Medial sagittal axis configuration.

2.4. Data acquisition and processing

Gait analysis for each subject was performed at the Biorobotics and Biomechanics Lab (BRML) of the Faculty of Mechanical Engineering at Technion-Israel Institute of Technology. Surface EMG ZeroWire system (Aurion Ltd., 10–4000 Hz, 16 bit resolution on all measurements) was used to record the muscle activity of lower limb muscles. The activity of all the following muscles was recorded: lateral gastrocnemius (LG), medial gastrocnemius (MG), vastus lateralis (VL), vastus medialis (VM), tibialis anterior (TA), semitendenosis (ST), and biceps femoris (BF). The EMG recording electrodes were bipolar, disposable, pre-gelled Ag/AgCl surface electrodes (Noraxon USA Inc.). Each electrode was fixed properly to each muscle belly by an experienced physician according to the "surface EMG for non-invasive assessment of muscles" (SENIAM) recommendations for surface EMG placement (Merletti and Hermens, 2000).

The EMG data was collected while the subjects walked over a 10 m walkway at a self-selected velocity. A metronome was used to ensure consistent cadence throughout the trial. Six walks at each configuration were collected per subject for averaging. In the therapy program investigation, six walks while barefoot were collected per subject for averaging both before therapy and after the therapy program. The EMG signals were sampled at 240 Hz and then exported to MATLAB™ for data processing.

The EMG envelopes were calculated according to standard procedures (Langzam et al., 2006; Nigg et al., 2006). First, a high pass filter of 10 Hz (Butterworth, 4th order) was carried out to remove motion artifacts. The signal was then rectified and the peak envelope was extracted. A low pass filter of 15 Hz (Butterworth, 4th order) was then carried out. Similarly to Clancy et al. (2004), the onset and termination of muscle contraction was defined as the instant when the envelope increased or decreased from the baseline activity. The detection was carried out manually by a trained physician. To avoid any bias in marking onset and termination times, the signals were randomly presented to the observer on a normalized time scale. The physician was blind to the source of the file (before or after training, identity of the subject, etc.). Manual muscle activation detection was found to be more valid then the detection by a computerized analysis system (Di Fabio, 1987).

Each step was divided into stance and swing, as measured by the force plates (AMTI OR6-7-1000). All calculations were performed for the stance phase. The time scale of the stance was normalized from 0% to 100%. The stance period was divided into several phases with respect to time: initial contact (IC; 0–2%), load response (LR; 0–10%), midstance (MS; 10–30%), terminal stance (TS; 30–50%), preswing (PS; 50–60%) and terminal contact (TC; 60–100%) (Perry, 1992). The EMG data for each leg was analyzed separately. The data for the more symptomatic knee leg, as selected by the patient, was termed the 'more symptomatic leg' the other leg was termed the 'less symptomatic leg'.

2.4.1. Parameters calculated in the COP manipulation investigation

Using a protocol similar to Edwards et al. (2008) an average rectified value (ARV) for the EMG of each muscle during each phase of the stance period was obtained by calculating the integral of the graph pertaining to a specific phase. The integral value was then divided by the time duration of the segment. The EMG activity of each muscle during each phase of stance was compared in four configurations of the device: control, neutral, medial and lateral. Within subject EMG normalization was not needed because participants acted as their own control and all procedures were performed in the same session (Edwards et al., 2008; Soderberg and Knutson, 2000).

2.4.2. Parameters calculated in the training program investigation

The EMG activity of each muscle during each phase of stance of barefoot walking was compared before and after three months of therapy. In addition to ARV, a normalized activity duration (NAD) was calculated as the time from initiation to termination of activation normalized to the gait cycle time, and a peak activity (PA) value was calculated as the peak value of the EMG envelope during stance. Since the electrodes had to be reapplied to the patients at the end of therapy, some differences in the EMG signal could have arisen that were not caused by the therapy itself. To minimize these differences between the baseline and endpoint, the system calibration and electrodes placement before and after therapy were kept identical. In addition, all subjects acted as their own control and each muscle was compared to itself. Normalization of the EMG data could therefore only affect the magnitude but not the consistency of the results and, consequently, was not applied in the pre- to post-training comparison.

2.5. Statistical analysis

In the COP manipulation investigation, Friedman tests were used to determine statistically significant differences in the ARVs of all subjects in different gait stages between the control, neutral, medial and lateral configurations, and post hoc tests were calculated for subgroup comparisons by the Wilcoxon non-parametric test adjusting for p-value smaller than 0.05. In the therapy program investigation, Wilcoxon tests were used to compare significant changes between the pre- and post-training parameters. A probability of less than or equal to 0.05 was considered as statistically significant. All analyzes were performed by a biostatistician using SPSS (version 13.0).

3. Results

3.1. COP manipulation

In the COP manipulation investigation, the ARV in each of the six phases of stance was compared in four COP configurations: lateral, medial, neutral and control. In the less symptomatic leg, almost all muscles varied significantly with COP in at least one phase of stance. Specifically, there were significant differences in ARV across the COP configurations for the lateral gastrocnemius in the midstance ($p < 0.001$), terminal stance ($p < 0.001$), preswing ($p = 0.001$) and terminal contact ($p < 0.001$) phases, for the tibialis anterior in the terminal stance ($p = 0.039$), for the medial gastrocnemius in the loading response ($p = 0.011$), for the biceps femoris in the midstance ($p = 0.007$) and terminal stance ($p = 0.005$) phases and for the semitendenosis in the terminal stance ($p = 0.028$). In the more symptomatic leg, significant differences in ARV across the COP configurations for the lateral gastrocnemius were found in the terminal stance ($p = 0.005$), preswing ($p = 0.002$) and terminal contact ($p = 0.032$) phases of stance, for the tibialis anterior in the preswing ($p = 0.010$) and for the vastus lateralis in the initial contact ($p = 0.050$). The results are presented in Table 1.

When the lateral gastrocnemius was examined specifically, it was found that the highest ARV values were observed for medial COP shifts, and the lowest ARV values were observed for lateral COP shifts. The ARV at the neutral COP fell between these two extremes and the ARV at the control configuration fell slightly below that of the neutral configuration (Fig. 2). The application of post hoc tests to the lateral gastrocnemius of the less symptomatic leg revealed significant differences between the medial and lateral

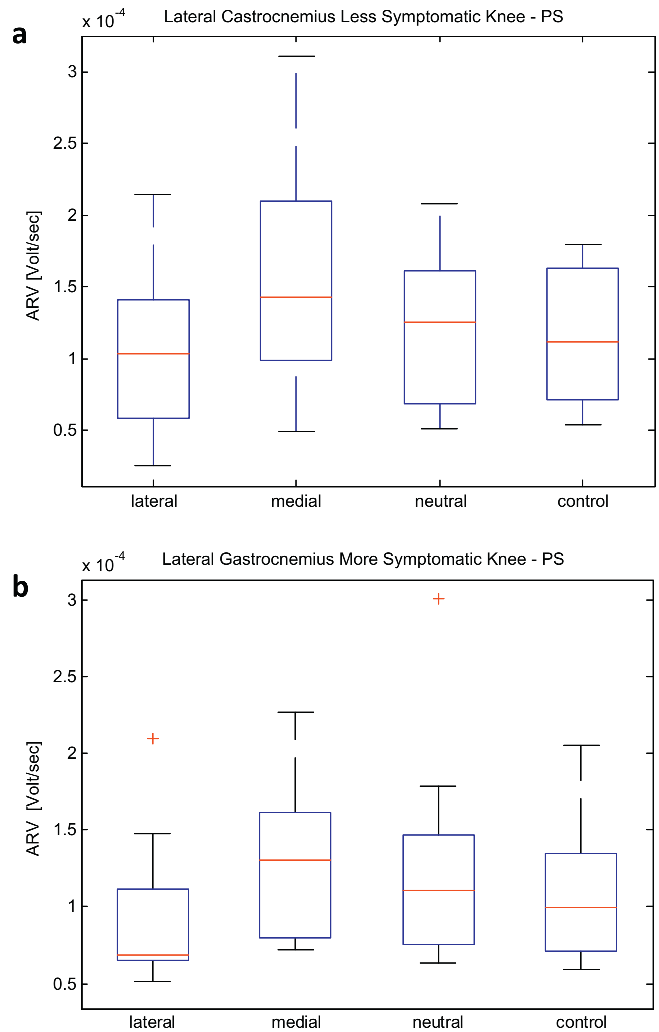

Fig. 2. Average rectified EMG values for the lateral gastrocnemius muscle during the preswing (PS) phase of stance in box plots (a) less symptomatic; (b) more symptomatic knees. Lateral, medial, neutral and control represent the four COP configurations examined. *(+) = outlier.

Table 1
The average rectified values (mean (SD) [10^{-4} V/s]) for each lower limb muscle in specific phases of stance compared across center of pressure configurations.

	More symptomatic						Less symptomatic				
	Lateral	Medial	Neutral	Control	p value		Lateral	Medial	Neutral	Control	p value
LG (MS)	0.83 (0.43)	0.98 (0.52)	0.96 (0.62)	0.78 (0.47)	0.094	LG (MS)	1.10 (0.58)	1.35 (0.56)	1.18 (0.45)	0.86 (0.36)	<0.001*
LG (TS)	0.64 (0.27)	0.90 (0.33)	0.87 (0.34)	0.74 (0.34)	0.005*	LG (TS)	0.80 (0.38)	1.12 (0.35)	0.95 (0.31)	0.91 (0.35)	<0.001*
LG (PS)	0.93 (0.46)	1.26 (0.50)	1.25 (0.67)	1.09 (0.42)	0.002*	LG (PS)	1.06 (0.54)	1.57 (0.72)	1.20 (0.50)	1.15 (0.44)	0.001*
LG (TC)	0.71 (0.33)	1.20 (0.41)	1.10 (0.34)	0.99 (0.37)	0.032*	LG (TC)	1.02 (0.26)	1.37 (0.43)	1.24 (0.32)	1.23 (0.40)	<0.001*
TA (MS)	1.48 (1.04)	1.42 (1.04)	1.41 (0.84)	1.28 (0.73)	0.972	TA (MS)	1.25 (0.60)	1.17 (0.58)	1.22 (0.47)	0.99 (0.41)	0.053
TA (TS)	0.76 (0.56)	0.74 (0.54)	0.71 (0.52)	0.69 (0.47)	0.677	TA (TS)	0.65 (0.36)	0.59 (0.28)	0.48 (0.31)	0.38 (0.37)	0.039*
TA (PS)	0.41 (0.31)	0.65 (0.45)	0.57 (0.33)	0.48 (0.26)	0.010*	TA (PS)	0.31 (0.27)	0.50 (0.32)	0.27 (0.26)	0.36 (0.23)	0.052
MG (LR)	0.74 (0.51)	0.82 (0.67)	0.90 (0.72)	0.64 (0.49)	0.197	MG (LR)	1.14 (0.98)	0.94 (0.66)	0.76 (0.52)	0.94 (1.04)	0.011*
BF (MS)	0.63 (0.35)	0.87 (0.52)	0.87 (0.59)	0.74 (0.48)	0.272	BF (MS)	0.71 (0.44)	1.14 (0.71)	0.75 (0.39)	0.79 (0.71)	0.007*
BF (TS)	0.33 (0.23)	0.39 (0.25)	0.42 (0.30)	0.38 (0.25)	0.457	BF (TS)	0.31 (0.18)	0.53 (0.38)	0.37 (0.26)	0.31 (0.30)	0.005*
ST (TS)	0.41 (0.23)	0.77 (1.24)	0.46 (0.20)	0.37 (0.19)	0.195	ST (TS)	0.33 (0.36)	0.38 (0.26)	0.21 (0.15)	0.26 (0.16)	0.028*
VL (IC)	0.66 (0.38)	0.60 (0.31)	0.68 (0.36)	0.81 (0.38)	0.050*	VL (IC)	0.56 (0.19)	0.65 (0.23)	0.73 (0.34)	0.77 (0.37)	0.071
VL (MS)	1.30 (0.97)	1.26 (0.86)	1.43 (0.99)	1.42 (0.93)	0.356	VL (MS)	0.87 (0.41)	1.25 (0.80)	1.07 (0.52)	1.24 (0.79)	0.053

Notes: LG = lateral gastrocnemius; TA = tibialis anterior; MG = medial gastrocnemius; BF = biceps femoris; ST = semitendenosis; VL = vastus lateralis; IC = initial contact; LR = loading response; MS = mid-stance; TS = terminal stance; PS = pre-swing; TC = terminal contact.
* $p \leqslant 0.05$ was considered statistically significant.

Table 2
Clinical outcome via self-reported subjective questionnaires.

	Baseline	After 3 months	p value
WOMAC			
Pain	4.55 ± 2.30	1.71 ± 1.28	<0.001
Stiffness	5.84 ± 3.41	2.73 ± 2.07	0.0085
Function	4.88 ± 2.37	2.04 ± 1.52	<0.001

Notes: Outcome measures: Western Ontario and McMaster Osteoarthritis Index (WOMAC) questionnaire (0–10 cm scale). Mean values are presented as mean ± SD.

configurations in the terminal stance, preswing and terminal contact phases (all $p < 0.001$).

3.2. Training program

Patient self-reported WOMAC pain scores and function scores revealed a significant improvement after 3 months of training. Subjects reported significant pain relief with a mean difference of 2.84 cm (decreased by 64%, $p < 0.001$). On the WOMAC function scale, the subjects reported a significant improvement with a mean decrease of 2.84 cm (decreased by 51%, $p < 0.001$). The extent of improvement in the level of pain and function corresponded with the OARSI–OMERACT criteria for clinical response to treatment (Pham et al., 2004). The results are presented in Table 2.

A small but significant increase was found in the gait velocity (increase by 7.74%, from 1.03 ± 0.11 to 1.12 ± 0.13 m/s, $p = 0.012$) and step length (increase by 3.18%, from 0.58 ± 0.052 to 0.605 ± 0.06 m, $p = 0.006$) after training. No significant difference was found in the cadence.

All muscles measured in both limbs showed greater peak activity. The increase in activity was significant for the lateral gastrocnemius (increased by 144%; $p = 0.004$), vastus medialis (increased by 108%; $p = 0.006$), tibialis anterior (increased by 79%; $p = 0.004$), semitendenosis (increased by 112%; $p = 0.006$), and vastus lateralis (increased by 72%; $p = 0.026$) in the less symptomatic leg, and for the medial gastrocnemius (increased by 106%; $p = 0.050$) in the more symptomatic leg. The results are presented in Table 3.

All muscles in the less symptomatic leg showed a lower normalized activity duration after three months of training. The decrease was significant only for the lateral gastrocnemius (decreased by 17%; $p = 0.006$). In the more symptomatic leg, the normalized activity duration of the tibialis anterior, medial gastrocnemius and biceps femoris decreased after the training but the normalized activity duration of the lateral gastrocnemius, vastus medialis, semitendenosis and vastus lateralis increased. A statistically significant difference was found only for the biceps femoris (decreased by 14%; $p < 0.001$). These results are presented in Table 3.

An illustration of EMG adaptation for the lateral gastrocnemius muscle in the less symptomatic leg after training for one subject is presented in Fig. 3. This figure demonstrates the increase in peak activity and decrease in normalized activity duration after training.

The ARV of all muscles in almost all phases of stance increased in both legs after 3 months of training. This change was significant for the less symptomatic leg in the lateral gastrocnemius during loading response ($p = 0.032$), midstance ($p = 0.003$) and terminal stance ($p = 0.033$) (average increase by 69%), in the vastus medialis during initial contact ($p = 0.002$), loading response ($p = 0.024$), midstance ($p = 0.030$), terminal stance ($p = 0.042$), and preswing ($p = 0.013$) (average increase by 48%), in the tibialis anterior during loading response ($p = 0.042$), midstance ($p = 0.012$) and terminal stance ($p = 0.034$) (average increase of 48%) and in the semitendenosis during initial contact ($p = 0.042$), loading response ($p = 0.011$), terminal stance ($p = 0.024$) and terminal contact ($p = 0.020$) (average increase by 51%). For the more symptomatic leg the change was significant in the lateral gastrocnemius during preswing ($p = 0.024$) (increase by 30%), in the vastus medialis during terminal stance ($p = 0.014$), preswing ($p = 0.002$) and terminal contact ($p = 0.010$) (average increase by 66%), in the tibialis anterior during preswing ($p = 0.042$) (increase by 40%), in the medial gastrocnemius during initial contact ($p = 0.037$) and loading response ($p = 0.027$) (average increase by 50%) and in the semitendenosis during initial contact ($p = 0.024$) (increase by 70%). These results are presented in Table 4.

4. Discussion

The influence of COP manipulation and perturbation therapy program (AposTherpy) on muscle activation in medial knee OA patients was investigated in this study. Although several studies have reported on the benefits of this novel training in knee OA patients before (Elbaz et al., 2010; Bar-Ziv et al., 2010), the influence of the training on muscle activation had not yet been examined. The present study consisted of two parts. First the study aimed to measure lower limb muscle activation changes in knee OA patients in response to four COP configurations. Second, the study aimed to measure barefoot lower limb muscle activation before and after a 3-month gait perturbation-training program with a patient-specific COP configuration.

In the first part of the study, the ARV of all muscles in the less symptomatic leg varied significantly with COP in at least one phase of stance. In the more symptomatic leg, significant ARV changes with COP were observed for the lateral gastrocnemius, tibialis anterior and vastus lateralis. When examining the lateral

Table 3
The peak activity (PA) (mean (SD) [10^{-4} V/s]) and normalized activity duration (NAD) (mean (SD) [10^{-1} s]) for muscles of the lower limb before and after 3 months of training.

	More symptomatic							Less symptomatic						
	LG	VM	TA	MG	BF	ST	VL	LG	VM	TA	MG	BF	ST	VL
PA														
Baseline	4.40 (3.17)	4.26 (6.38)	3.86 (2.86)	5.05* (3.94)	2.13 (1.26)	4.03 (3.36)	2.81 (2.41)	3.39* (1.50)	2.32* (2.17)	4.30* (2.83)	6.30 (8.89)	3.01 (2.84)	2.75* (1.91)	1.89* (1.09)
3 Months	5.10 (4.61)	4.67 (3.81)	5.23 (5.13)	10.4* (8.51)	4.09 (5.86)	7.04 (8.31)	4.37 (4.17)	8.26* (8.74)	4.83* (2.98)	7.71* (6.37)	9.60 (7.71)	6.47 (7.22)	5.83* (4.77)	3.25* (1.31)
NAD														
Baseline	4.65 (1.03)	3.98 (0.81)	2.22 (0.94)	4.28 (1.08)	4.27* (0.89)	3.41 (1.02)	4.06 (1.08)	5.04* (0.83)	3.83 (0.80)	1.85 (0.74)	5.30 (0.37)	3.92 (0.78)	3.88 (1.11)	4.07 (0.79)
3 Months	4.67 (0.92)	4.07 (1.17)	1.97 (0.69)	3.83 (1.41)	3.73* (1.0)	3.46 (0.68)	4.17 (1.25)	4.42* (0.93)	3.49 (0. 97)	1.85 (0.81)	4.05 (1.46)	3.79 (0.85)	3.56 (0.71)	3.51 (0.70)

Notes: LG = lateral gastrocnemius; TA = tibialis anterior; MG = medial gastrocnemius; BF = biceps femoris; ST = semitendenosis; VL = vastus lateralis; VM = vastus medialis.
* $p \leqslant 0.05$ was considered statistically significant.

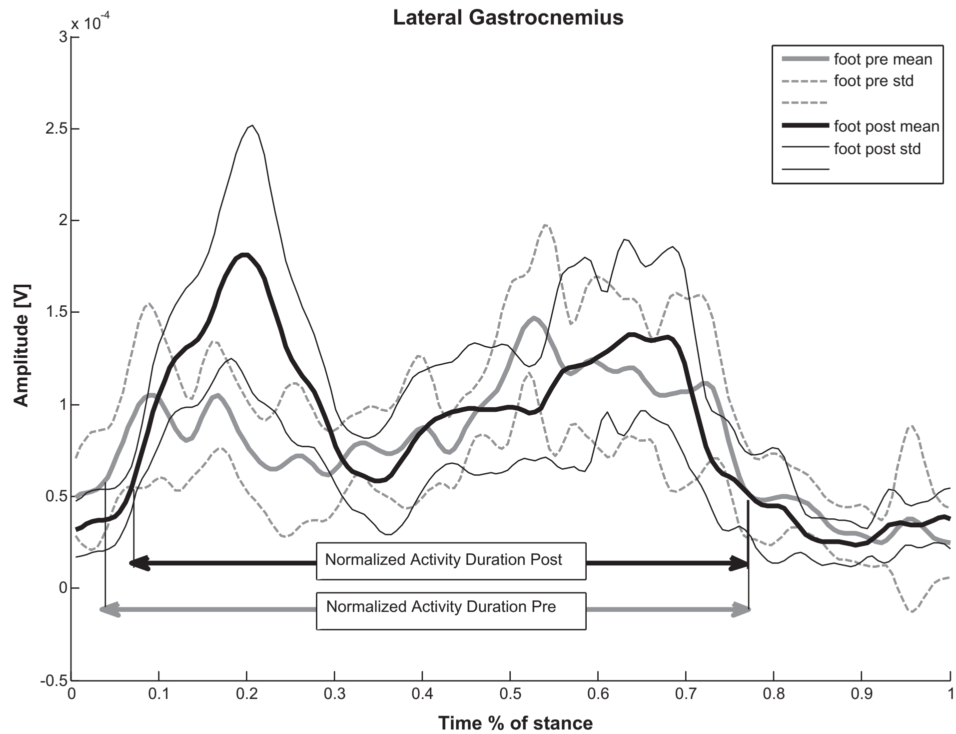

Fig. 3. Electromyographic changes in the lateral gastrocnemius in the less symptomatic leg for one subject before and after 3 months of training. The EMG amplitude is presented over time (percent of stance). The thick gray line is the mean amplitude before therapy and the thick black line is after therapy. The dashed gray lines are standard deviation before therapy and the thin whole black lines are after therapy. The normalized activity duration (NAD) is presented as well.

gastrocnemius muscle specifically, it was observed that its ARV EMG increased substantially when the COP was shifted medially and decreased substantially when the COP was shifted laterally (Fig. 2). This change was also observed in our previous study on healthy individuals (Goryachev et al., 2011). This observation can be explained by the kinetic changes with COP reported by Haim

Table 4
The average rectified values (mean (SD) [10^{-4} V/s]) for each lower limb muscle in specific phases of stance before and after 3 months of training.

Phase of stance	More symptomatic leg					Less symptomatic leg				
	LG	VM	TA	MG	ST	LG	VM	TA	MG	ST
IC										
Baseline	0.47 (0.37)	1.99 (3.85)	1.62 (0.61)	0.70 (1.0)	0.79 (0.33)	0.44 (0.34)	0.56 (0.36)	2.01 (0.72)	0.48 (0.41)	0.95 (0.47)
3 Months	0.62 (0.47)	1.89 (2.76)	2.40 (1.37)	1.27 (1.35)	2.72 (4.14)	2.20 (4.11)	1.32 (0.74)	2.83 (2.28)	0.80 (1.10)	1.67 (1.17)
p	0.267	0.232	0.168	0.037*	0.024*	0.109	0.002*	0.204	1	0.042*
LR										
Baseline	1.61 (1.56)	2.41 (3.98)	2.47 (1.3)	1.66 (2.36)	1.29 (0.77)	1.20 (1.05)	0.99 (0.64)	3.15 (1.77)	1.09 (1.18)	1.21 (0.65)
3 Months	1.91 (2.58)	2.35 (3.11)	4.01 (3.41)	3.84 (4.33)	3.14 (4.15)	3.82 (5.18)	1.88 (0.93)	4.84 (3.67)	2.73 (3.63)	2.54 (1.84)
p	0.903	0.232	0.094	0.027*	0.153	0.032*	0.024*	0.042*	0.562	0.011*
MS										
Baseline	2.03 (2.24)	1.53 (1.60)	1.51 (1.66)	2.74 (2.81)	1.60 (1.49)	1.28 (0.93)	1.30 (1.65)	1.12 (0.62)	2.74 (4.02)	0.98 (0.90)
3 Months	2.13 (2.57)	2.47 (1.80)	1.82 (1.16)	5.40 (4.59)	3.24 (4.70)	4.96 (7.19)	1.76 (0.76)	2.26 (2.45)	5.21 (4.82)	0.27 (2.33)
p	0.952	0.084	0.376	0.084	0.426	0.003*	0.030*	0.012*	0.562	0.008*
TS										
Baseline	1.21 (0.95)	0.64 (0.45)	0.59 (0.43)	1.24 (0.47)	0.51 (0.44)	0.98 (0.30)	0.69 (0.67)	0.31 (0.29)	1.58 (1.31)	0.78 (1.10)
3 Months	1.24 (0.69)	1.23 (0.88)	0.81 (0.48)	1.65 (1.03)	1.34 (2.12)	2.89 (3.94)	1.32 (1.30)	0.74 (0.51)	2.57 (1.18)	1.83 (2.18)
p	0.715	0.014*	0.168	0.695	0.426	0.033*	0.042*	0.034*	0.218	0.024*
PS										
Baseline	1.35 (0.52)	0.22 (0.19)	0.39 (0.27)	1.32 (0.72)	0.21 (0.28)	1.43 (0.63)	0.37 (0.36)	0.29 (0.24)	1.59 (1.31)	0.37 (0.55)
3 Months	1.92 (1.10)	0.93 (0.84)	0.65 (0.36)	1.30 (0.81)	0.20 (0.20)	2.74 (2.69)	1.11 (1.90)	0.39 (0.41)	2.14 (0.48)	0.79 (1.27)
p	0.024*	0.002*	0.042*	0.695	1	0.216	0.013*	0.638	0.093	0.358
TC										
Baseline	1.02 (0.28)	0.16 (0.09)	0.36 (0.22)	0.98 (0.42)	0.13 (0.14)	1.21 (0.47)	0.31 (0.26)	0.30 (0.21)	1.24 (0.51)	0.17 (0.13)
3 Months	1.39 (0.75)	0.61 (0.72)	0.40 (0.22)	1.17 (0.84)	0.21 (0.21)	1.61 (0.84)	0.73 (0.98)	0.33 (0.18)	1.44 (0.50)	0.43 (0.43)
p	0.268	0.010*	0.455	0.557	0.216	0.340	0.153	0.677	0.437	0.020*

Notes: LG = lateral gastrocnemius; TA = tibialis anterior; MG = medial gastrocnemius; BF = biceps femoris; ST = semitendenosis; VM = vastus medialis; IC = initial contact; LR = loading response; MS = mid-stance; TS = terminal stance; PS = pre-swing; TC = terminal contact.
* $p \leqslant 0.05$ was considered statistically significant.

et al. (2011). Their study reports that a medial COP shift increases the knee adduction moment. It is therefore logical to assume that the lateral gastrocnemius activity would increase in a medial COP shift in order to counteract this moment. The EMG changes in the first part of the study were also greater for the distal muscles of the lower limb. This observation is supported by the previous study on healthy individuals, which also showed greater changes in the distal muscles (mostly in the lateral gastrocnemius and tibialis anterior) with COP than in the proximal muscles (Goryachev et al., 2011).

In the second part of the study, the ARV of almost all muscles significantly increased in at least one phase of stance in both legs after 3 months of therapy. All muscles in both legs also showed greater peak activity (significant increase in the lateral gastrocnemius, tibialis anterior, vastus medialis, semitendenosis and vastus lateralis in the less symptomatic leg, medial gastrocnemius in the more symptomatic leg). This supports the initial hypothesis that muscle activity would increase with training. These findings are also supported by previous studies that reported an increase in the muscular activity after training in subjects with OA (Suetta et al., 2004; Graham and Fisher, 2003; Tal-Akabi et al., 2007). In addition, the training led to a lower duration of activity in most of the muscles examined. A quicker force development is necessary to maintain daily stability in ambulation and to prevent falling (Suetta et al., 2004). In a previous study, Childs et al. (2004) showed that OA subjects tend to have longer muscle activation than healthy subjects. For subjects with one healthy leg and one leg affected by OA, von Tscharner and Valderrabano (2010) showed that the activation timing of most of the examined muscles was earlier in the OA leg than in the healthy one. An additional study by Suetta et al. (2004) found that strength training increased the rate of contractile force development in subjects after hip replacement procedure. In light of these findings, it is reasonable to assume that the patients in the present study developed a healthier muscle activation strategy after therapy.

Another interesting observation was that the less symptomatic leg showed greater changes than the more symptomatic leg in both parts of the study. This observation is supported by a previous study that reported that healthy individuals consistently showed more significant increases in EMG activity than knee OA patients when treated with exactly the same resistance training program (Graham and Fisher, 2003).

The self-reported measurements (WOMAC) significantly improved after training, with patients reporting reduced pain and stiffness and greater function. Increased gait velocity and step length were also observed after training. In addition, these changes were associated with improved kinetic and kinematic parameters, the most prominent of which were reduction in knee adduction moment magnitude and increased range of motion at the knee, this data will be published in the future. Our findings support the findings of other studies that also showed improvements in gait parameters, pain, function and quality of life in knee OA patients treated with this form of therapy (Elbaz et al., 2010; Bar-Ziv et al., 2010).

There are several limitations to the present study. Firstly, the study cohort was relatively small. Secondly, since no normalization procedure on the data was performed, the ARV and peak EMG values are valid for this study only and cannot be compared to other studies. However, there was a consistent increase of ARV and peak EMG after training for almost all examined muscles, so it is reasonable to assume that it was induced by the training and not by the varying factors of signal acquisition. Lastly, the current study focused specifically on females with medial compartment knee OA and therefore the results are applicable only to subjects with characteristics similar to those of the study group.

5. Conclusions

COP manipulation directly influences the muscle activation patterns of the lower limb in patients with knee OA, in addition the present study has shown that, when patient-specific COP manipulation is combined with a 3-month perturbation gait-training program (AposTherapy), the EMG activity of the lower limb muscles increases and the duration of muscle activity decreases overall, leading to more normal activation patterns.

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Further reading

Haim A, Rubin G, Rozen N, Goryachev Y, Wolf A. Modification of gait patterns in knee osteoarthritis via non-invasive biomechanical training: a longitudinal gait analysis study, submitted for publication.

Yulia Goryachev received her BSc in Biomedical Engineering at the Technion-I.I.T. in 2006. Currently she is an MSc student at the Biorobotics and Biomechanics Lab (BRML) at Mechanical Engineering faculty at the Technion-I.I.T. Her research focuses in locomotion biomechanics with emphasis on the kinetics, kinematics and electromyography of the lower limb during gait.

Eytan M. Debbi was born and raised in New York, USA. He was graduated summa cum laude, Phi Beta Kappa from Yale University with a Bachelor's degree in Biology and Biotechnology. He is currently pursuing his Medical Degree at Tel Aviv University Sackler School of Medicine and his PhD at the Biorobotics and Biomechanics Lab (BRML) at Mechanical Engineering faculty at the Technion-I.I.T. His research interests include biomechanics, biorobotics, biomedical engineering, biotechnology and musculoskeletal disorders.

Amir Haim obtained his MD degree from the Technion-I.I.T in 2003. He is currently a PhD student at the Biorobotics and Biomechanics Lab (BRML) at Mechanical Engineering faculty at the Technion-I.I.T. and a resident in the department of orthopedic surgery in the Tel Aviv medical center. His research focuses in gait biomechanics with emphasis on plasticity of locomotor patterns and gait conditioning via controlled biomechanical intervention.

Nimrod Rozen, MD, PhD earned all his academic degrees from the Bruce Rappaport Faculty of Medicine, Technion-I.I.T. He is a senior lecturer at the Bruce Rappaport Faculty of Medicine, Technion-I.I.T, since 2008. He is currently the head of the Orthopaedic Surgery Department Ha'Emek Medical Center. Afula, Israel. His research interests include rehabilitation techniques in the field of orthopedics.

Alon Wolf, PhD, earned all his academic degrees from the Faculty of Mechanical Engineering at Technion-I.I.T. In 2002, he joined the Robotics Institute of Carnegie Mellon University and the Institute for Computer Assisted Orthopaedic Surgery as a member of the research faculty. He was also an adjunct Assistant Professor in the School of Medicine of the University of Pittsburgh. In 2006, he joined as the Faculty of Mechanical Engineering at Technion, where he founded the Biorobotics and Biomechanics Lab (BRML). The scope of work done in the BRML provides the framework for fundamental theories in kinematics, biomechanics and mechanism design, with applications in medical robotics, rehabilitation robotics, and biorobotics, such as snake robots.