Clinical Chiropractic (2006) 9, 59–69

Clinical Chiropractic

intl.elsevierhealth.com/journals/clch

Effect of an orthotic intervention on sensorimotor integration mechanisms in patients with musculoskeletal disorders

Jeanmarie R. Burke *

Biodynamics Laboratory, New York Chiropractic College Research, Seneca Falls, 2360 State Route 89, NY 13148, USA

Received 5 August 2005; accepted 2 November 2005

KEYWORDS
Adult humans;
Neuromuscular responses;
Orthotic interventions;
Proprioception

Summary

Objective: The objective of this research was to determine the effect of an orthotic intervention on the recruitment profiles of the tibial nerve H-reflex response in patients with musculoskeletal disorders during quiet standing as compared to lying prone on a table. The amount of H-reflex inhibition between resting prone and quiet standing assesses the integrity of sensorimotor integration mechanisms.
Design: Cross-sectional with repeated measures on footwear conditions for patients with musculoskeletal disorders. Single-blind of investigator for footwear conditions.
Setting: Research Laboratory.
Methods: The participants were 12 asymptomatic individuals and 11 patients with musculoskeletal disorders. In the prone and standing positions, H/M recruitment profiles were generated with subjects wearing their aerobic shoes. The subjects rested prone on a treatment table with their feet resting on foot plates. During quiet standing trials, subjects balanced equally on both feet while maintaining a relaxed posture and lightly grasping a hand support at hip level to minimize the influence of postural sway and fatigue. The patients were tested with and without their orthotics inserted into their aerobic shoes. The tibial nerve H-reflex methodology was used to record M-wave and H-reflex responses from the gastrocnemius muscle of the right leg. The H_{max}/M_{max} ratio was calculated from the recruitment profile in each test position.
Results: The amount of H-reflex inhibition for the prone position to quiet standing did not systematically increase with the orthotic intervention (12.7%) as compared to the patient's normal shoe condition (13.2%). Regardless of footwear condition, the amount of H-reflex inhibition from the prone position to quiet standing was similar to the effect observed in the asymptomatic individuals (13.4%). Among the patients

* Tel.: +1 315 568 3869; fax: +1 315 568 3204.
E-mail address: jburke@nycc.edu.

doi:10.1016/j.clch.2005.11.001

with musculoskeletal disorders, subject-specific variations in the amount of H-reflex inhibition from the prone position to quiet standing were significantly different from zero, between the two footwear conditions (5.7%; $t_{10} = 4.54$).
Conclusion: Altering sensory feedback signals from the plantar surface of the foot with an orthotic intervention modified sensorimotor integration mechanisms in a subject-specific manner. In agreement with biomechanics research and neuromuscular concepts for the benefits of orthotics, sensorimotor integration mechanisms may be different for each subject-shoe-insert condition.

Introduction

Subject-specific reactions to shoe orthotics appear to reflect the concept that the neuromechanical system of an individual has a preferred movement pattern for a motor task that is pre-programmed.[1–3] The preferred movement pattern reflects the most efficient motor response by an individual. The preferred movement pattern depends upon the unique characteristics of the musculoskeletal system of an individual, which include the resonant frequency of the soft tissue package, joint stiffness, and joint geometry, and accounts for inter-subject variations within categories of movements, e.g. gait activities and jumping exercises.[1,3] An orthotic intervention that supports the preferred movement path will enhance neuromuscular efficiency whereas orthotic intervention that counteracts the preferred movement path will decrease neuromuscular efficiency.[1,3] Improvements in neuromuscular efficiency with an optimal orthotic intervention will manifest as a reduction in muscle activity, which may contribute to an increase in comfort perception.[1,3] This theoretical paradigm characterizes the neuromuscular concepts for the benefits of orthotics.

In accordance with neuromuscular concepts for the benefits of orthotics,[1,3] an optimal orthotic may improve sensorimotor integration mechanisms. Sensorimotor integration mechanisms at the levels of the spinal cord, brainstem and cerebral cortex modulate motor outputs via regulating sensory feedback signals. Orthotics act as second-order filters in the transduction of impact forces by cutaneous receptors on the plantar surface of the foot.[1,3] Effective dampening of soft tissue vibration by orthotics may reduce muscle activity, minimize fatigue, and increase comfort perception.[1,3,4] Thus, an optimal orthotic intervention may improve neuromuscular efficiency by influencing sensorimotor integration mechanisms. From a practical perspective, sensorimotor integration mechanisms account for variations in motor responses generated by the neuromuscular system and reflect the particular sensory information received by the central nervous system for a given movement task, e.g. variations in gait patterns when walking on even and uneven surfaces.

Evidence for the relationship between altered sensory feedback signals from the plantar surface of the feet and modulation of motor outputs is essential knowledge to implicate the role of sensorimotor integration mechanisms for the benefits of orthotics. Recent research addressed the effects of altered foot sensation on plantar pressure and muscle activity during walking. The data indicated that sensory feedback signals from cutaneous receptors on the plantar surface of the foot regulate the distribution of plantar pressures and muscle activation patterns during walking.[5] The contribution of sensory feedback signals to motoneuronal drive during walking is summarized by Nielsen and Sinkjaer.[6]

There is other evidence substantiating the contribution of sensory feedback signals to the control of human gait. Increased sensitivity of the hallux to high frequency vibration is associated with higher peak pressures under the hallux while running and walking.[7] During running, lower mean vibration thresholds at 125 Hz for the plantar surfaces of the foot (increased sensitivity to high frequency vibrations) are associated with higher mean peak pressures distributed across the plantar surfaces of the foot.[7] Although these data are counterintuitive to the regulation of impact forces for injury prevention during gait, the data emphasize the importance of sensory feedback signals to the control of human gait.[7]

The research of Nigg and colleagues suggested that altering the sensory feedback signals from the plantar surface of the foot with orthotics may allow for systematic changes in muscle activation patterns.[1,5,8] Despite these relationships between altered sensory feedback signals and modulation of motor outputs, the effects of orthotics on the basic mechanisms of sensorimotor integration have not been directly tested to date. It is also hypothesized that functional groups of patients my produce similar reactions to specific orthotic interventions.[1,2] Preferred footwear conditions are those

Table 1 Characteristics of the participants (mean ± standard deviations)

Groups	Gender	Age (years)	Height (cm)	Weight (kg)
Asymptomatic	6 males 6 females	27.8 ± 5.27	170.2 ± 11.20	80.2 ± 26.81
Musculoskeletal disorders	9 males 2 females	28.5 ± 5.56	179.9 ± 9.29	87.9 ± 19.43

in which the lowest level of leg pain or back pain is experienced during standing tasks.[9] Empirically, individuals easily identify comfortable and uncomfortable footwear and clinicians use comfort as a criterion to rate the appropriateness of orthotic interventions. Thus, patients with musculoskeletal disorders of the lower extremity and lower back, who rate an orthotic intervention as comfortable, may be an appropriate functional group to study the effects of foot orthotics on the basic mechanisms of sensorimotor integration.

The objective of this research was to determine the effect of an orthotic intervention on the recruitment profiles of the tibial nerve H-reflex response in patients with musculoskeletal disorders during quiet standing as compared to lying prone on a table. The tibial nerve H-reflex is the electrically evoked neural correlate of the mechanically evoked Achilles tendon reflex. As compared to the recruitment profile evoked in the prone position, the electromyographic (EMG) amplitudes of the H-reflex responses are tonically depressed during quiet standing in asymptomatic individuals.[10] The inhibition of the H-reflex response in standing man, as compared to the prone position, reflects the regulation of sensory feedback mechanisms by the central nervous system.[10] In other words, the amount of H-reflex inhibition between resting prone and quiet standing assesses the integrity of sensorimotor integration mechanisms.

Methods

Participants and experimental design

The participants were 12 asymptomatic individuals and 11 patients with musculoskeletal disorders. Table 1 summarizes characteristics of the participants. Although the patients with musculoskeletal disorders did not report any clinical disabilities, the patients did chose to wear an orthotic intervention to address their conditions. The patients self-reported their musculoskeletal disorders as persistent in nature. The patients were required to wear the orthotic intervention for a duration of at least 1 month and to perceive the orthotic intervention as more comfortable than their normal shoe condition. Table 2 summarizes the musculoskeletal disorders and the duration of the orthotic intervention.

The duration of orthotic intervention was not being controlled, because the criterion underlying the beneficial effects of the orthotic intervention was comfort perception. In accordance with the neuromuscular concept for the benefits of orthotics, if the patient perceives the orthotic as comfortable, then improvements in sensorimotor integration are likely. The rationale for the 1-month "break-in" period was to allow for neuromuscular adaptations to the orthotic intervention. The underlying assumption was that the orthotic intervention maintains the integrity of sensorimotor integration, after the initial "break-in" period. Based on the rationale and underlying assumption for this research, the retrospective (>2 months) and prospective (<2 months) inclusion of patients with orthotic interventions was a function of the duration of orthotic intervention and not a confounding aspect of the experimental design. The duration of the orthotic intervention was recorded to ensure that it was not a confounding variable.

Table 2 Summary of musculoskeletal disorders and duration of orthotic intervention for the participants

Musculoskeletal disorders	Duration of orthotic intervention (months)
Flat feet	1
Pain: knees and lower back	1
Prevent heel spurs, lower back pain	1
Leg length inequality (lower left hip)	1
Lower back pain	8
Lower back pain, forefoot cushioning	1.5
Lower back pain	24
Pronation of both feet	6
Lower back pain, pronation of both feet	12
Lower back pain	5
Lateral knee pain during running	18

Note: Oswestry Disability Index did not detect any clinical disability in the subjects reporting lower back pain.

Table 3 Experimental design

Groups	Experimental conditions	Testing positions	
		Prone position	Quiet standing
Asymptomatic	Normal shoe	*H*/*M* recruitment curve	*H*/*M* recruitment curve
Musculoskeletal Disorders	Normal shoe	*H*/*M* recruitment curve	*H*/*M* recruitment curve
	Orthotic + shoe	*H*/*M* recruitment curve	*H*/*M* recruitment curve

Note: The investigator was blinded to the orthotic intervention by having an administrative assistant randomly determine the order of experimental conditions.

For the asymptomatic individuals, the recruitment profiles were generated with the individuals in their normal shoe condition. The recruitment profiles of the patients with musculoskeletal disorders were generated for their normal shoe condition and again with their orthotic intervention. The normal shoe condition required the subjects to wear the shoes that they perceived as most comfortable for aerobic activities. The orthotic intervention was inserted into these same shoes for the patients with musculoskeletal disorders. The orthotic intervention was the flexible, custom-made orthotics by Foot Levelers, Inc. (Roanoke, VA, USA). Table 3 summarizes the experimental design.

The data from the asymptomatic individuals established normative values for the amount of H-reflex inhibition from the prone position to quiet standing and provided internal validity for our measurement protocol. The physiologic effect of the orthotic intervention on sensorimotor integration was evaluated in the patients with musculoskeletal disorders using a repeated measures experimental design. The investigator was blinded to the orthotic intervention by having an administrative assistant randomly determine the order of experimental conditions. There was no need to blind the patient as the patient cannot voluntarily control the recruitment profiles. Within the experimental protocol, background muscle activity, arousal states, and body positions were standardized for the normal shoe condition and orthotic intervention. As such, changes in recruitment profiles between the experimental conditions reflected the effects of the orthotic intervention on sensorimotor integration.

Measurement protocols

H-reflex methodology

The tibial nerve H-reflex methodology outlined by Hugon[11] was used to record M-wave and H-reflex responses from the gastrocnemius muscle (GM) of the right leg. Electrical stimulation of a peripheral nerve, e.g. the tibial nerve in the popliteal fossa, at low stimulus intensities preferentially recruits Ia afferents and evokes a monosynaptic reflex response with a latency of 30 ms on average, H-reflex response. With increasing stimulation intensity, the alpha motoneuron axons are activated producing a direct muscle response with a latency of 5 ms on average, M-wave response. The *H*/*M* recruitment curve describes the activation of the Ia afferents (H-reflex amplitude) and alpha motoneuron axons (M-wave amplitude) as a function of stimulus intensity. The maximal M-wave amplitude represents activation of entire alpha motoneuron pool. The H/M_{max} ratio reflects the proportion of the alpha motoneuron pool recruited by Ia afferents.

The specific stimulation and recording parameters were as follows. The right tibial nerve was stimulated in the popliteal fossa using a 1.0 ms square wave pulse delivered by a constant voltage stimulator (Grass S88, Grass Instruments, W. Warwick, RI, USA). The cathode-stimulating electrode (10 mm self-adhesive, pre-gelled, Ag—AgCl) was positioned within the popliteal fossa at the optimal location for evoking a H-reflex in the GM. The optimal location for the cathode was defined as the site within the popliteal fossa at which a slightly suprathreshold stimulus for evoking a H-reflex did not evoke a M-wave response. The anode stimulating electrode was placed 10 cm proximal to the cathode on the posterior thigh. The electromyographic (EMG) response of the GM was recorded using 10 mm bipolar self-adhesive, pre-gelled, surface disposable Ag—AgCl electrodes. The Braddom and Johnson[12] methodology of electrode configuration was used to ensure consistent placement of recording electrodes over the GM across subjects. The EMG signal was bandpass filtered (10 Hz—10 kHz) and amplified using an EMG amplifier system (Grass P511, Grass Instruments, W. Warwick, RI, USA).

Recruitment profiles

EMG amplitudes, peak-to-peak EMG values, of the H-reflex and M-wave responses were the dependent variables. The *H*/*M* recruitment profile was generated by increasing stimulus intensity from subthreshold to maximal in 5—10 V increments. The typical M-wave recruitment curve is S-shaped;

whereas, the typical H-reflex recruitment curve is an inverted "U". In order to define the maximal H-reflex response, stimulus intensity was increased in 5 V increments within the range of ±30 V from the apex of the H-reflex recruitment curve. Three trials were recorded for each stimulation voltage. After determining the maximal H-reflex response, stimulus intensity was then increased on consecutive trials in 10 V increments until the maximal M-wave was evoked. The maximal M-wave response was defined as the plateau in EMG amplitude that occurred in response to three successive 10 V increments of stimulus intensity.

Testing positions

The subjects rested *prone* on a treatment table with their feet resting on foot plates. The foot plates were rotated to maintain 90° angles at the ankle joint in order to control for the effects of muscle length on H-reflex responses. Postural effects on H-reflex responses were accounted for by having the subjects rest their head face down on the treatment table with their arms placed down by their sides onto arm rests. The arms were bent at 90° angles at the elbow joint and the head piece on the treatment table allowed for the subject to rest comfortably face down. The subjects were visually observed for gross changes in arousal states.

During *quiet standing* trials, subjects balanced equally on both feet while maintaining a relaxed posture. The subjects lightly grasped a hand support at hip level to minimize the influence of postural sway and fatigue. The symmetrigraf posture chart was used to ensure that subjects maintained a constant relaxed posture across trials and footwear conditions. Markings on the floor were used to align the feet and to ensure consistent foot placements across trials and footwear conditions. Background EMG records from the GM and tibialis anterior muscles were used to ensure similar background levels of muscle activity across trials and footwear conditions.

Comfort perception

Visual analog scale (VAS) is a reliable indicator of footwear comfort when orthotic conditions are compared to a control condition during a physical activity such as running.[13,14] Preferred footwear conditions are those in which the lowest level of leg pain or back pain is experienced during standing tasks.[9] Thus, VAS may be the most appropriate index of comfort perception when studying the physiologic effects of orthotic interventions. Using the VAS methodology of Mundermann et al.,[13] the subjects rated the footwear comfort of their normal shoe condition. The context of administrating the 150 mm VAS required that the subjects rate the footwear comfort of their normal shoe condition for performing aerobic activities such as walking, prolonged standing, or running with anchors set at not comfortable at all to the most comfortable imaginable. The patients with the musculoskeletal disorders also rated the footwear comfort of their orthotic intervention within this context. In addition, the patients with musculoskeletal disorders rated their low back pain using the Oswestry Disability Questionnaire.[15,16]

Statistical analyses

The dependent variable for each testing position and each experimental condition was the H_{max}/M_{max} ratio. For the asymptomatic individuals, a *t*-test of H_{max}/M_{max} ratios between the testing positions was used to document the amount of H-reflex inhibition from the prone to standing postures. Using the normal shoe condition, a Group × Testing Position mixed ANOVA model was used to compare the amount of H-reflex inhibition between the patients with musculoskeletal disorders and asymptomatic individuals as a function of testing positions.

Table 4 Ratings of footwear comfort (means ± standard deviations)

Categories	Asymptomatic	Musculoskeletal disorders	
	Normal shoe	Orthotic intervention	Normal shoe
Overall comfort	114.4 ± 23.40	114.3 ± 26.16	93.7 ± 30.70
Heel cushioning	116.8 ± 22.96	112.5 ± 27.32	92.5 ± 29.42
Forefoot cushioning	111.8 ± 24.39	109.9 ± 27.92	91.0 ± 28.09
Medial-lateral control	109.5 ± 23.71	102.8 ± 34.62	85.4 ± 25.15
Arch height	106.9 ± 30.08	106.3 ± 30.25	77.7 ± 29.93
Heel cup	120.4 ± 23.73	107.9 ± 25.25	89.4 ± 36.51
Heel width	119.7 ± 23.76	112.5 ± 28.26	94.3 ± 30.92
Forefoot width	116.8 ± 21.86	109.2 ± 28.51	86.4 ± 29.07
Length	126.0 ± 23.00	116.0 ± 24.62	104.3 ± 26.59

Ratings of footwear comfort: 150 mm VAS from not comfortable at all to the most comfortable imaginable.

For patients with musculoskeletal disorders, an Experimental Condition × Testing Position repeated measures ANOVA model was used to reveal changes in amount of H-reflex inhibition from the prone position to quiet standing as a function of footwear condition. The amount of H-reflex inhibition between footwear conditions was assessed using the difference from zero at the 5% confidence level of significance. This post hoc analysis allowed us to determine subject-specific responses to the orthotic intervention.

A single factor repeated measures MANOVA was used to compare footwear comfort as function of the orthotic intervention for the patients with musculoskeletal pain disorders. The univariate F tests at a significance level of .005 (.05/9) were used to determine differences for the various aspects of footwear comfort (Table 4).

Results

Comfort perception

Table 4 summarizes the ratings of footwear comfort. The overall comfort ratings of 114 mm in this study for an aerobic shoe by asymptomatic individuals was in agreement with previous literature for a standard running shoe.[13,14] For patients with musculoskeletal disorders, the Wilks' Lambda criterion for multivariate tests of significance was not significant for the different aspects of footwear comfort between the normal shoe condition and orthotic intervention. Patients with musculoskeletal pain disorders rated their orthotic intervention as more comfortable than their normal shoe condition ($p < .005$). The orthotic intervention significantly improved arch height support, heel cushioning and forefoot cushioning ($p < .005$). Medial-lateral stability ($p = .017$), heel cup fit ($p = .013$), heel width ($p = .007$), forefoot width ($p = .023$) and length ($p = .058$) were not significantly different between the orthotic intervention and normal shoe condition. In general, the orthotic intervention increased the ratings of footwear comfort from the normal shoe condition to the ratings by the asymptomatic individuals for their aerobic shoes.

Recruitment curves for asymptomatic individuals

The amount of H-reflex inhibition from the prone position to quiet standing was 13.4% ($t_{11} = 6.72$, $p < .05$). During quiet standing, there was an inhibition of the H_{max}/M_{max} ratio in all 12 subjects, which ranged from 2.6% to 26.9%. Fig. 1A summarizes these data. The EMG amplitudes of the maximal M-wave response (33.7 ± 6.24 mV versus 32.5 ± 4.96 mV) and the recruitment profiles (Fig. 1B) were similar for the prone position and the quiet standing position, respectively. The 95% confidence interval for the maximal M-wave responses was from 30.9 mV to 35.3 mV. These data indicate that the EMG recording environment was maintained throughout the test session. Thus, the amount of H-reflex inhibition from the prone position to quiet standing reflected the modulation of Ia afferent activity by sensorimotor integration mechanisms.

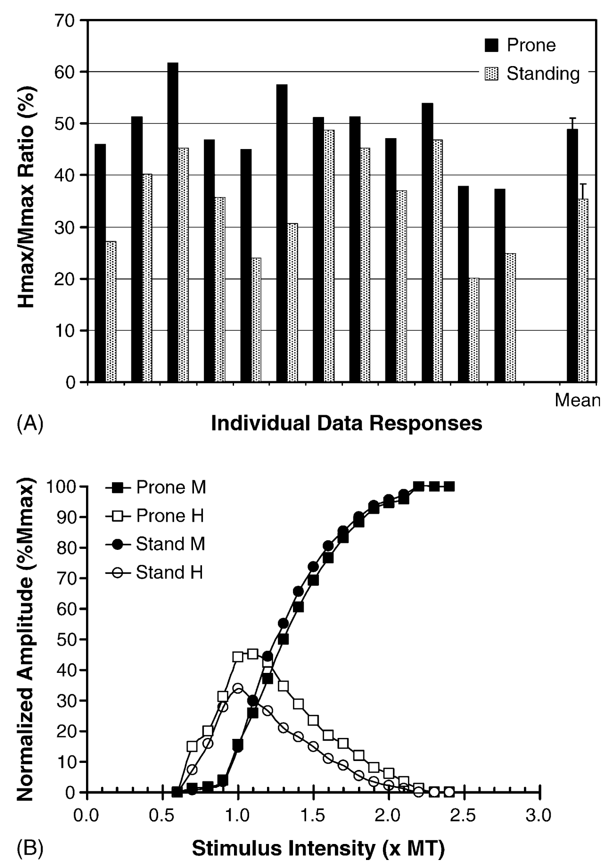

Figure 1 (A) H_{max}/M_{max} ratios for each of the asymptomatic subjects and the group mean as a function of test position: prone or quiet standing. The error bars for the group means represent the standard errors of the means. (B) H/M Recruitment curve averaged across the asymptomatic subjects. Stimulus intensity was normalized to motor threshold for each subject. Error bars were not included, as the purpose of the graph was to depict the similar recruitment profiles for the prone position and the quiet standing position. The similar recruitment profiles and maximal M-wave responses indicated that the H-reflex response was modulated from the prone position to the quiet standing position.

Recruitment curves for patients with musculoskeletal pain disorders

The amount of H-reflex inhibition for the prone position to quiet standing did not systematically increase with the orthotic intervention (12.7%) as compared to the patient's normal shoe condition (13.2%). Regardless of footwear condition, the amount of H-reflex inhibition from the prone position to quiet standing was similar to the effect observed in the asymptomatic individuals (Fig. 2). During quiet standing, there was an inhibition of the H_{max}/M_{max} ratio in all 11 patients, which ranged from 1.8% to 27.6% with the orthotic intervention (Fig. 3A) and from 2.6% to 29.9% in the normal shoe condition (Fig. 3B).

The EMG amplitudes of the maximal M-wave response were consistent for each posture and for each footwear condition. The 95% confidence interval for the maximal M-wave responses was from 32.8 mV to 36.7 mV. The recruitment profiles were similar for the prone position and the quiet standing position and for each of the footwear conditions (Fig. 4). There was no statistical order effect ($F_{[1,10]} = 0.65$). During quiet standing, averaged background EMG from the gastrocnemius and tibialis anterior muscles were consistent across both footwear conditions. These data indicate that the EMG recording environment was maintained throughout the test session and that the data responses reflected the effects of the footwear conditions on the modulation of Ia afferent activity by sensorimotor integration mechanisms.

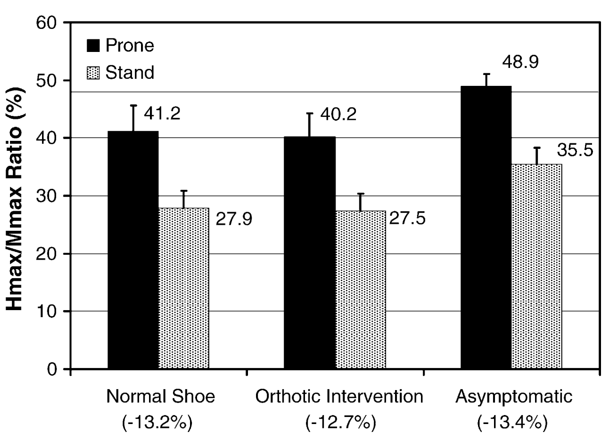

Figure 2 Comparisons of the H_{max}/M_{max} ratios for the patients with musculoskeletal disorders between footwear conditions and to the asymptomatic individuals as a function of test position: prone or quiet standing. The error bars represent the standard errors of the means. The values in parentheses represent the amount of inhibition of the H-reflex response from prone to quiet standing.

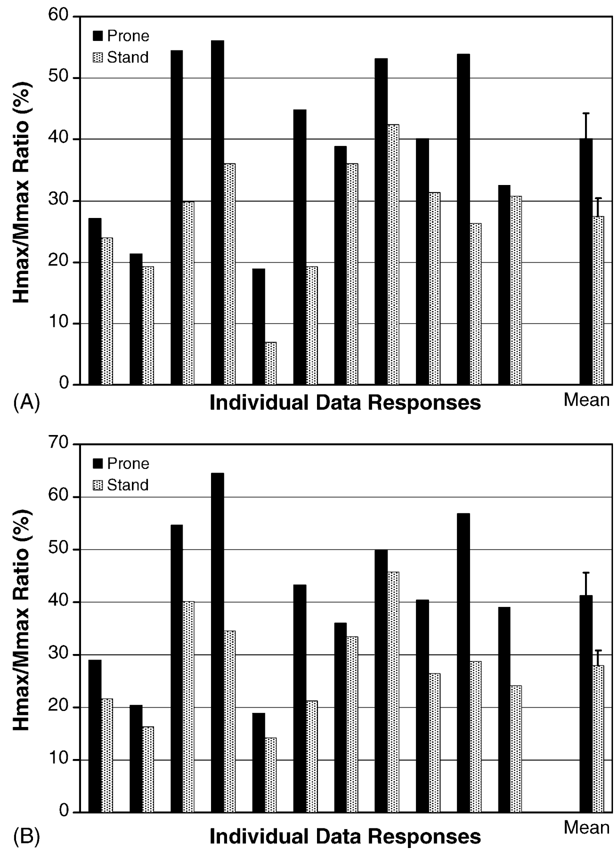

Figure 3 (A) H_{max}/M_{max} ratios with the orthotic intervention for each of the patients with musculoskeletal disorders and the group mean as a function of test position: prone or quiet standing. The error bars for the group means represent the standard errors of the means. (B) H_{max}/M_{max} ratios in the normal shoe condition for each of the patients with musculoskeletal disorders and the group mean as a function of test position: prone or quiet standing. The error bars for the group means represent the standard errors of the means.

Subject-specific responses

Subject-specific variations in the amount of H-reflex inhibition from the prone position to quiet standing were significantly different from zero, between the two footwear conditions (5.7%; $t_{10} = 4.54$, $p < .05$; Fig. 5). Differences of H_{max}/M_{max} ratios in the prone position were also significantly different from zero, between the two footwear conditions (2.6%; $t_{10} = 3.28$, $p < .05$). However, between footwear conditions, the subject-specific variations in amount of H-reflex inhibition (5.7%) were significantly greater than for the differences of H_{max}/M_{max} ratios in the prone position (2.6%; $t_{10} = 2.60$, $p < .05$). Subject-specific responses were independent of the duration and perceived comfort of the orthotic intervention (Fig. 6). Collectively, these data indicate that

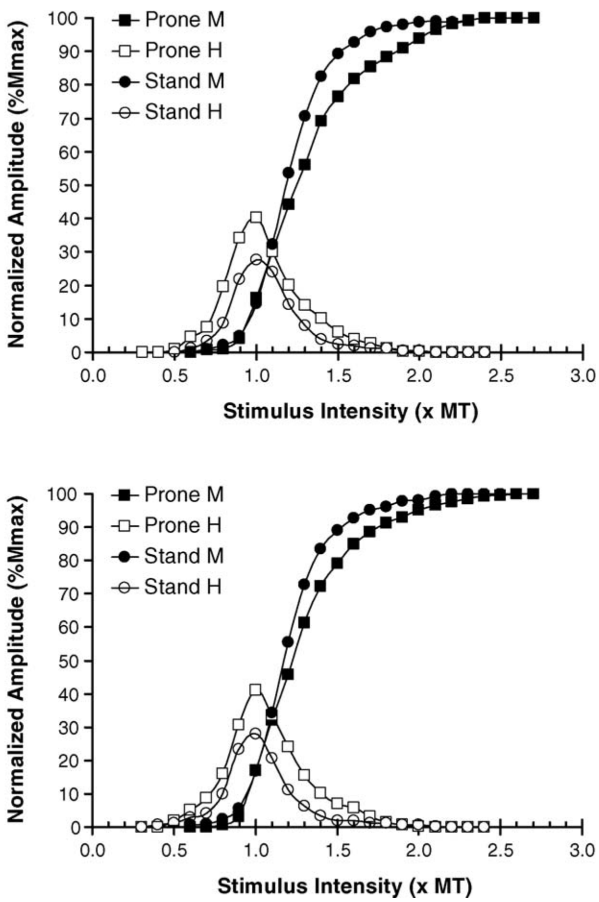

Figure 4 *H*/*M* recruitment curve averaged across the patients with musculoskeletal pain disorders: Top panel: orthotic intervention and bottom panel: normal shoe condition. Stimulus intensity was normalized to motor threshold for each subject and each footwear condition. Error bars were not included, as the purpose of the graph was to depict the similar recruitment profiles for the prone position and the quiet standing position in each footwear condition. The similar recruitment profiles and maximal M-wave responses indicated that the H-reflex response was modulated from the prone position to the quiet standing position in each footwear condition.

subject-specific variations in the amount of H-reflex inhibition from the prone position to quiet standing reflected significant differences of sensorimotor integration mechanisms between the two footwear conditions.

Discussion

Although the orthotic intervention was perceived as comfortable by all patients with musculoskeletal disorders, the orthotic intervention did not systematically increase the modulation of Ia afferent activity by sensorimotor integration mechanisms. The inhibition of the H-reflex response during quiet standing as compared to the prone position was similar in patients with musculoskeletal disorders and in asymptomatic individuals. The data were consistent with normative values previously reported in the literature for healthy young adults.[10] However, altering sensory feedback signals from the plantar surface of the foot with an orthotic intervention modified sensorimotor integration mechanisms in a subject-specific manner. Subject-specific responses are also observed in biomechanical research on the benefits of orthotic interventions.[1–3]

Subject-specific reactions to orthotic interventions are the norm.[2,17,18] Subject-specific reactions to orthotic interventions appear to reflect the concept that the neuromechanical system of an individual depends upon the resonant frequency of the soft tissue package, sensitivity of mechanoreceptors, and preferred movement control patterns.[1,19] A better understanding of the function of orthotics may be revealed by addressing comfort perception, neuromuscular efficiency and performance within the theoretical paradigm of the neuromuscular concepts for the benefits of orthotics.[1,19]

The central nervous system regulates variations in sensory input signals, which are related to the impending impact forces and resonant frequency of the soft-tissue package, via feedforward control mechanisms.[4,20] There is an increase in the intensity of anticipatory EMG activity of leg muscles with increasing impact loading rates as demonstrated from pendulum experiments[4] and during overground running.[4,20] Anticipatory EMG activities of the lower extremity reflect muscle tuning strategies used by the central nervous system to minimize soft tissue vibrations.[20–22] Mechanoreceptors of the plantar surface of the feet act as third-order filters for the force-input signal to further minimize soft tissue vibrations during the post-impact period.[3,19]

The potential consequences of undamped soft tissue vibrations are impairments to neuromuscular efficiency.[3,19] The resonant frequency of the soft tissue package and sensitivity of mechanoreceptors are subject-specific whereas shoe cushioning affects the loading rates of impact forces.[3,19] Besides impact control of soft tissue vibrations, individuals have preferred movement patterns for motor tasks that are pre-programmed.[1,19] Consequently, feedforward muscle tuning strategies, sensory feedback mechanisms, and movement control patterns may be different for each subject-shoe-insert condition.[1,19] Thus, the benefits of an optimal orthotic intervention will be improvements in neuromuscular efficiency, which is strongly influenced by subject-specific characteristics.

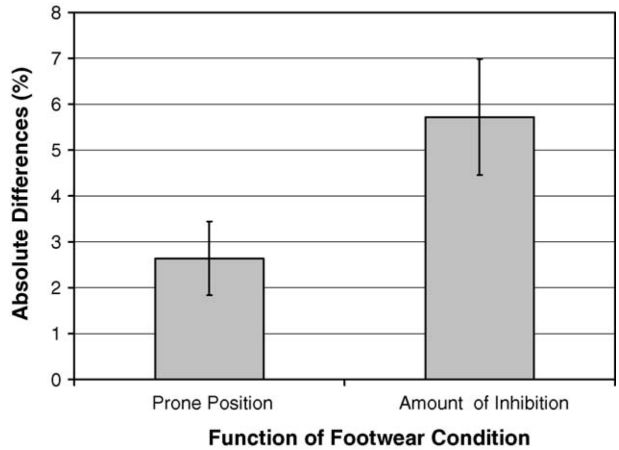

Figure 5 The amount of H-reflex inhibition between footwear conditions was assessed using the difference from 0 at the 5% confidence level of significance. Variations of H_{max}/M_{max} ratios in the prone position between footwear conditions were also assessed using the difference from 0 at the 5% confidence level of significance. The error bars represent the standard errors of the means.

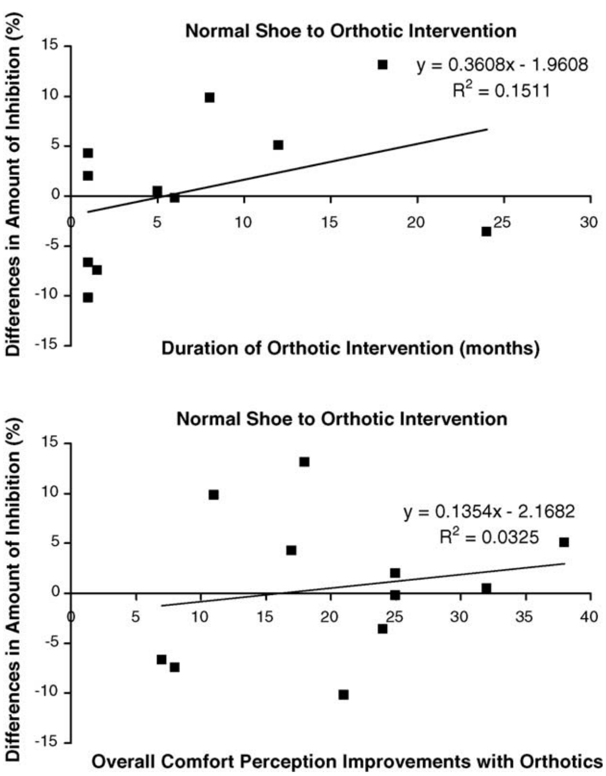

Figure 6 Among patients with musculoskeletal disorders, regression analyses determined the influences of the duration of orthotic intervention (top panel) and overall comfort perception (bottom panel) on the amount of H-reflex inhibition. Differences in the amount of H-reflex inhibition from normal shoe condition to the orthotic intervention were calculated. Increases in amount of H-reflex inhibition from normal shoe condition to the orthotic intervention are negative values; decreases in amount of H-reflex inhibition from normal shoe condition to the orthotic intervention are positive values.

Improvements in neuromuscular efficiency with an optimal orthotic intervention will manifest as a reduction in muscle activity and oxygen consumption and increased comfort perception during physical activity.[1,3,19] Preliminary data indicate that orthotic interventions may influence oxygen consumption during steady-state runs at slightly above aerobic threshold.[3,17] However, more systematic evaluations of running economy with orthotic interventions, and consequently neuromuscular efficiency, still need to be addressed.

The relationship of comfort perception to changes in lower extremity kinematics, kinetics, and muscle activity was evaluated in 21 recreational runners.[8] Although 15 kinematic, kinetic, and EMG variables could only account for 34.9% of the variance in comfort perception, these same 15 variables classified 75% of running trials correctly to the corresponding footwear condition.[8] Based upon the presentation of the data, it was difficult to determine if the EMG intensity of each of seven muscles decreased with increasing comfort perception. However, the negative β weights for the majority of significant EMG variables suggest an inverse relationship between muscle activity and comfort perception. Specifically, the β weights are standardized regression coefficients that are used to predict a response outcome, e.g. comfort perception, from a set of measured variables, e.g. EMG activities from multiple muscles, and a negative sign indicates an inverse relationship. These data tentatively support the concept that decreased muscle activity contributes to comfort perception of orthotics during physical activity.[8] However, support of the neuromuscular concepts for the beneficial effects of orthotics is still lacking sufficient evidence.

Our data findings indicate that altering sensory feedback signals from the plantar surface of the foot with an orthotic intervention modified sensorimotor integration mechanisms in a subject-specific manner. However, the modulation of sensory feedback signals with the orthotic intervention was independent of comfort perception. Consequently, the effects of orthotic interventions on sensorimotor integration mechanisms may be related to either the sensitivity of mechanoreceptors of the human foot or the processing of sensory feedback signals by the central nervous system, which are subject-specific. This latter physiologic interpretation of our data is consistent with the hypothesis that subject-specific reactions to orthotic interventions reflect individual variations in resonant frequency of the soft tissue package, sensitivity of mechanoreceptors, and preferred movement control patterns.[1,19] Thus, the regulation of neuromuscular efficiency with an orthotic intervention also depends upon the integrity of sensorimotor integration mechanisms.

Although subject-specific reactions to orthotic interventions are still the norm,[2,17,18] it is also hypothesized that functional groups of patients with similar neuromechanical characteristics and clinical case presentations may produce similar reactions to specific orthotic interventions.[1,2,19] Future research needs to incorporate other criteria, beyond comfort perception, to rate the appropriateness of orthotic interventions. Among our patients with musculoskeletal disorders, variations in their neuromechanical characteristics and clinical case presentations may have prevented us from detecting systematic increases in the modulation of Ia afferent activity by sensorimotor integration mechanisms. Chronic low back patients may be a more appropriate functional group to study the effects of foot orthotics on the basic mechanisms of sensorimotor integration as improvements in the Quebec Back Pain Disability Index occurred following an intervention with custom-made foot orthotics.[23] However, it may also be necessary to identify subgroups of chronic low back patients based upon neuromechanical characteristics and clinical case presentations.

Evidence on the more dominant effects of custom-molding as compared to posting is also available with respect to the lower extremity kinematics and kinetics during running.[24] Molding of the orthotic is deemed more important than postings with respect to ratings of comfort perception.[8] These data do not address which specific structural component of foot orthotics is more beneficial for injury reduction and human performance.[24] However, if increasing comfort and improving neuromuscular efficiency are important functions of foot orthotics, then foot orthotics should be custom-molded and constructed with softer materials.[8,13,24] Both of these key properties are construct components of Foot Levelers orthotics that were used in this research. As such, testing the beneficial effects of Foot Levelers orthotics from a neuromuscular perspective as a function of comfort perception seemed appropriate.

Conclusions

Altering sensory feedback signals from the plantar surface of the foot with an orthotic intervention modified sensorimotor integration mechanisms in a subject-specific manner. These data are consistent with theoretical paradigm of the neuromuscular concepts for the benefits of orthotics.[1,19] Identifying the relationship between mechanoreceptor sensitivity of the feet and the integrity of sensorimotor integration mechanisms may provide further insights on regulation of neuromuscular efficiency with an orthotic intervention.

Acknowledgments

The author acknowledges the financial support of Foot Levelers, Inc. and the engineering contributions of Mr. Owen Papuga. Leslie Freeman assisted with the recruitment of subjects from the Seneca Falls Health Centers.

References

1. Nigg BM, Nurse MA, Stefanyshyn DJ. Shoe inserts and orthotics for sport and physical activities. *Med Sci Sports Exerc* 1999; **31**:S421—8.
2. Nigg BM, Stergiou P, Cole G, Stefanyshyn DJ, Mundermann A, Humble N. Effect of shoe inserts on kinematics, center of pressure, and leg joint moments during running. *Med Sci Sports Exerc* 2003;**35**:314—9.
3. Nigg BM, Wakeling JM. Impact forces and muscle tuning: a new paradigm. *Exerc Sport Sci Rev* 2001;**29**:37—41.
4. Wakeling JM, von Tscharner V, Nigg BM, Stergiou P. Muscle activity in the leg is tuned in response to ground reaction forces. *J Appl Physiol* 2001;**91**:1307—17.
5. Nurse MA, Nigg BM. The effect of changes in foot sensation on plantar pressure and muscle activity. *Clin Biomech* 2001;**16**: 719—27.
6. Nielsen JB, Sinkjaer T. Afferent feedback in the control of human gait. *J Electromyogr Kinesiol* 2002;**12**:213—7.
7. Nurse MA, Nigg BM. Quantifying a relationship between tactile and vibration sensitivity of the human foot with plantar pressure distributions during gait. *Clin Biomech* 1999;**14**:667—72.
8. Mundermann A, Nigg BM, Humble RN, Stefanyshyn DJ. Orthotic comfort is related to kinematics, kinetics, and

EMG in recreational runners. *Med Sci Sports Exerc* 2003; **35**:1710—9.

9. Basford JR, Smith MA. Shoe insoles in the workplace. *Orthopedics* 1988;**11**:285—8.
10. Koceja DM, Trimble MH, Earles DR. Inhibition of the soleus H-reflex in standing man. *Brain Res* 1993;**629**:155—8.
11. Hugon M. Methodology of the Hoffmann Reflex in man. In: Desmedt JE., editor. *New developments in electromyography and clinical neurophysiology*. Basel: Karger; 1973. p. 277—93.
12. Braddom RI, Johnson EW. Standardization of H reflex and diagnostic use in S1 radiculopathy. *Arch Phys Med Rehabil* 1974;**55**:161—6.
13. Mundermann A, Nigg BM, Stefanyshyn DJ, Humble RN. Development of a reliable method to assess footwear comfort during running. *Gait Posture* 2002;**16**:38—45.
14. Mundermann A, Stefanyshyn DJ, Nigg BM. Relationship between footwear comfort of shoe inserts and anthropometric and sensory factors. *Med Sci Sports Exerc* 2001;**33**: 1939—45.
15. Fairbank JC, Pynsent PB. The Oswestry Disability Index. *Spine* 2000;**25**:2940—52.
16. Roland M, Fairbank J. The Roland-Morris Disability Questionnaire and the Oswestry Disability Questionnaire. *Spine* 2000; **25**:3115—24.
17. Nigg BM, Stefanyshyn D, Cole G, Stergiou P, Miller J. The effect of material characteristics of shoe soles on muscle activation and energy aspects during running. *J Biomech* 2003;**36**:569—75.
18. Wakeling JM, Pascual SA, Nigg BM. Altering muscle activity in the lower extremities by running with different shoes. *Med Sci Sports Exerc* 2002;**34**:1529—32.
19. Nigg BM. The role of impact forces and foot pronation: a new paradigm. *Clin J Sport Med* 2001;**11**:2—9.
20. Boyer KA, Nigg BM. Muscle activity in the leg is tuned in response to impact force characteristics. *J Biomech* 2004; **37**:1583—8.
21. Wakeling JM, Nigg BM. Modification of soft tissue vibrations in the leg by muscular activity. *J Appl Physiol* 2001;**90**: 412—20.
22. Wakeling JM, Nigg BM, Rozitis AI. Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. *J Appl Physiol* 2002;**93**:1093—103.
23. Dananberg HJ, Guiliano M. Chronic low-back pain and its response to custom-made foot orthoses. *J Am Podiatr Med Assoc* 1999;**89**:109—17.
24. Mundermann A, Nigg BM, Humble RN, Stefanyshyn D. Foot orthotics affect lower extremity kinematics and kinetics during running. *Clin Biomech* 2003;**18**:254—62.