Plantar feedback contributes to the regulation of leg stiffness

P. Fiolkowski1,2, D. Brunt2, M. Bishop2, R. Woo3, M. Horodyski1

1Department of Exercise and Sport Science, University of Florida, Gainesville, Fl, USA
2Department of Physical Therapy, University of Florida, Gainesville, Fl, USA
3Department of Orthopedics, University of Florida, Gainesville, Fl, USA

Introduction
In running gait, the lower extremity behaves as a simple linear spring1, the stiffness of which remains fairly constant over a wide range of surface stiffness level. While the phenomenon has been observed and well reported, there has been no explanation for the basic mechanism by which people are able to adjust leg stiffness to a surface change. The alteration of leg stiffness with changes in sensory feedback fits in well with the neuromechanical control hypothesis2. In this hypothesis, it is emphasized that the role of reflexive neural feedback in a dynamic feedforward system will have an effect on the regulation of rapid rhythmic activity. By examining the role of afferent feedback and the effects on mechanical properties of the leg, i.e. stiffness, it may provide some measure of understanding the integration of neural and mechanical systems in legged locomotion.

Methods
10 volunteers, free from lower extremity pathology signed an Informed Consent, as approved by the University Institutional Review Board. An orthopedic surgeon administered a subdermal injection of 1% lidocaine with epinephrine in the area of the tibial nerve, immediately posterior and distal to the medial malleolus. An AMTI force plate was used for data collection. Data were collected at 1000Hz and filtered to remove electrical noise. The data was analyzed for peak vertical acceleration (a_z), ground contact time, and center of mass displacement.

The activities of rectus femoris, gastrocnemius, medial soleus, and tibialis anterior were recorded using surface electrodes. The raw data were band pass filtered from 20 to 350 Hz, and full wave rectified. The muscle activity was analyzed for time of muscle onset prior to ground contact, duration of muscle activity, maximal amplitude and mean amplitude. Sagittal plane kinematic data were collected at 50Hz, from retroreflective markers placed on the acromion, greater trochanter, lateral joint line of the knee, lateral malleolus and 5th metatarsophalangeal joint. Kinematic data were compared for angles of the knee and ankle at touchdown as well as the angles for maximal flexion during the stance phase of hopping.

In order to evaluate the effect of the block, Semmes–Weinstein monofilaments were used to evaluate sensory deficits, a pressure algometer for detection of deep pressure on the heel pad, and plantar intrinsic musculature surface EMG were examined pre- and post-injection. Functional stability was assessed using a Romberg test. Subjects hopped on a force plate at 2.2 Hz. All subjects were given as much time as necessary to practice the task and become accustomed to maintaining the rhythm. An electronic metronome maintained the rhythm with an audible timer.

Results
The block was determined effective due to significant changes noted in all four measurements used. There was a significant difference in monofilament testing for tactile sensation between conditions. (p<0.01) and an increase in the threshold to detection of pressure (p <0.01). The results of the changes in EMG from the plantar surface, specifically the abductor hallucis muscle, were consistent among all subjects. The integrated EMG in the anesthetic condition averaged 22.53% of the control value. Romberg testing following the injection increased the forces exerted in the mediolateral direction an average of 62% and in the anteroposterior direction, 52%. All subjects who demonstrated a loss of deep pressure feedback also had the highest values for postural sway.
Leg Stiffness: A repeated measures ANOVA revealed a significant decrease in leg stiffness between the 2 conditions (p<0.001) (Figure 1). The values for knee and ankle angle at the time of touchdown were compared between conditions for the subjects. However, it was noted that there was a difference in strategies between subjects when adapting to the loss of feedback. Some subjects demonstrated greater knee flexion, but no difference in knee flexion while others exhibited a greater value for ankle flexion. Therefore, we combined the 2 values in order to calculate an overall flexion value. Total flexion in the control condition was 56.47° compared to 63.28° in the anesthetized condition (p<0.001).

Muscle Activity: The gastrocnemius exhibited significantly later onset relative to touchdown in the anesthetized condition, when compared to the control condition (p<0.001). There was no difference in muscle duration between conditions. Similarly, the quadriceps demonstrated significant changes in timing between conditions (p < 0.01). In the control condition, the quadriceps had an earlier activation, while the duration of activation demonstrated no difference between conditions (Figure 2).

Discussion

Humans are capable of adjusting to a variety of conditions and speeds in locomotion. The regulation of the locomotor system allows for feedback to constantly adjust the system to optimize efficiency. The results of this experiment indicate that plantar feedback has a significant impact on regulating leg stiffness. The increases in flexion of the joints of the leg are consistent with the decreases seen in leg stiffness. With the increase in postural instability, as assessed by the Romberg test, it is safe to state that plantar feedback is important in maintaining postural stability. These results are consistent with the published works of Magnusson and Thoumie. It can be concluded from the results that the feedback from the sole of the foot is important in regulating load behavior in dynamic activities. The published results, supported by our tests, point to the role of plantar afferent feedback in maintaining postural stability.

In this experiment, we were able to observe changes in joint angles at touchdown, total ROM changes, and changes in muscle activation with the loss of plantar feedback. Our results differed from the previous authors in that there appear to be individual strategies for reacting to the deafferentation. While some subjects underwent a greater flexion at the knee during the landing phase, others experienced a greater ROM at the ankle. This is likely a reflection of different strategies used by the subjects to compensate for the loss of feedback.

While it was noted that all subjects exhibited a decrement in activity of the intrinsic musculature of the foot, as measured by the abductor hallucis this activity, such decrement did not always correspond to alterations in the kinetics measured. The numbers do not support a conclusive claim to a preferential role of pressure receptors over muscle afferents in the regulation of leg stiffness, and the ability to specifically ablate one nerve or the other has more to do with anatomical variation, i.e. the bifurcation of the tibial nerve. Yet this does provide some further insight into the role of the nervous system as it affects the mechanical properties of the leg. The results point to a dynamic coupling of the neural system with the mechanical properties of the leg and locomotor system. The neuromuscular mechanism responsible for the changes seen is linked, apparently, to the feedback from the plantar surface of the foot. While the role in static posture had been demonstrated, we now have empirical evidence to point to the neural regulation of mechanical properties in rapid dynamic activities.

References

Figure 1. Change in leg stiffness between control and anesthetized conditions.

Figure 2. A display of the Fz data with gastrocnemius and quadriceps muscle activation. The bottom 3 channels are control trials.

Channel 1: vertical GRF - anesthetized
Channel 2: gastrocnemius - anesthetized
Channel 3: quadriceps - anesthetized
Channel 4: vertical GRF -control
Channel 5: gastrocnemius - control
Channel 6: quadriceps - control