CAUSALITY IN THE FEEDBACK LOOP DURING BALANCING TASKS: INTERMITTENT CONTROL OF QUIET STANDING

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The aim of this study was to investigate the relationship between the timing of intermittent muscle activity and joint fluctuation and between intermittent muscle activity and joint torque output. Eight healthy male participants stood quietly on the force platform for 120 sec, while we measured angular displacements and joint torque of the ankle, knee, and hip in the sagittal plane. Surface electromyography from six leg muscles of each leg was also recorded to determine phasic muscle activation and deactivation for each muscle by using two low-pass filters. We found that muscle activation and deactivation periods were in accordance with joint position and velocity and were associated with torque fluctuations in the anatomical action direction. These results succeeded in experimentally visualizing the causality of the feedback loop of the postural control mechanism.

KEY WORDS: Electromyography, Posture, Inverse dynamics, Kinematics.

INTRODUCTION: Postural balancing ability is essential for improving performance in various sports. However, the neural-muscular-skeletal causality while maintaining upright posture is not yet fully understood because postural control tasks are aperiodic and non-stationary, leading to ambiguity in the definition of postural stability.

The multi-joint human body is controlled both passively and actively, and it is always exposed to gravitational force. The passive stiffness caused by joint viscoelasticity of the muscle-tendon-ligament is insufficient to compete with the gravitational toppling torque during quiet standing (e.g. Loram and Lakie, 2002). Therefore, human bipedal standing should be actively controlled through integrated sensory cues from the visual, vestibular, and somatosensory systems (Peterka, 2002).

Generally, human motor control systems must include continuous and intermittent processes. In the context of human bipedal standing, a continuous system, involving muscle spindle and Goldi tendon organ feedback, provides tonic equilibrium joint moments via tonic stretch reflexes (Sherrington, 1947). However, the continuous control strategy itself is insufficient to regulate the dynamics of the postural system (Marsden et al., 1981), and intermittency of the postural control mechanism plays an important role in the stabilization dynamics in the vicinity of the equilibrium.

In this study, we focus on the intermittent system of the postural feedback loop to visualize the causality among neural intermittent motor command triggering, muscle activities, and skeletal fluctuations. We extracted “on-period” and “off-period” from Electromyography (EMG) signals, which represent muscle activation and deactivation, respectively. Our results will show the neural-muscular-skeletal causality during aperiodic and non-stationary quiet standing. Once we find direct musculoskeletal relationships during standing in healthy adults, such findings will form the basis for evaluating the individual postural control mechanisms and balance skills for specific populations (such as athletes). The aim of this study was to investigate the direct relationship between intermittent muscle activity and joint fluctuation and between intermittent muscle activity and joint torque output.

METHODS: Eight healthy males participated in this study. Participants were instructed to stand quietly with their eyes open on a force platform for 120 sec. We collected data for five trials for each participant. One splint was strapped to the back of the participant at the forehead, chest, and pelvis to ensure correct triple inverted pendulum model approximation of quiet standing by allowing joint motions to occur around the ankle, knee, and hip joints. Joint motion data was obtained with a three-dimensional (3D) optical motion capture system with a sampling frequency of 100 Hz (OptiTrack V100:R2; NaturalPoint, Corvallis, OR). Spherical reflective markers were affixed to the lateral side of fifth

metatarsophalangeal (MP), ankle (lateral malleolus), knee (lateral condyle of femur), hip (greater trochanter), anterior superior iliac spine (ASIS), and shoulder (acromion) on both sides of the participants' body. Surface EMG over the rectus femoris (RF), long head of biceps femoris (BFL), medial gastrocnemius (MG), lateral gastrocnemius (LG), soleus (SOL), tibialis anterior (TA) were recorded from both legs with Ag-AgCl electrodes of 5 mm and an interelectrode distance of 20 mm. All EMG signals were stored with a sampling frequency of 2 kHz on the hard disk of a personal computer.
Time series of kinematics data from a motion capture system and the displacement of center of pressure (CoP) were passed through a second-order Butterworth low-pass filter with a cutoff frequency of 20 Hz. Coordinates of the hip were calculated using the maker location data of greater trochanter and ASIS (Kurabayashi et al., 2003). We then computed the joint angles and angular velocities of the ankle, knee, and hip in the sagittal plane (θ and ω). Joint torques were also calculated by inverse dynamics using vertical grand reaction force. Joint angles and torques were defined as positive in extension.
All EMG signals were first numerically rectified and processed by the second order Butterworth low-pass filter with a cutoff frequency of 12 Hz (rough EMG; rEMG). We determined phasic on/off switching of muscle activity (activation/deactivation) from rEMG data by using two low-pass filtered EMG signals, each of which represents phasic and tonic component of muscle activations. The second order Butterworth low-pass filter with a cutoff frequency of 0.02 Hz was applied to all rEMG signals to obtain trend curves, which represent tonic muscle activity components (Nomura et al., 2007). We also obtained smoothed rEMG (sEMG) signals by applying the second order Butterworth low-pass filter with a cutoff frequency of 2 Hz. We assumed that the trend curve subtracted from the sEMG signal represents phasic muscle activation. If the sEMG was above the trend curve for a time interval, we considered that the muscle activity was high (on-period) in that interval, otherwise, off-period.
We then divided the dynamics (time history) of a state point [θ, ω] in the phase planes of the ankle, knee, and hip joints into on and off periods (on and off area, respectively) for each 12 muscles for visualizing the relationship between phasic muscle activities and joint oscillations. Each on/off area was fit into a second order mixed Gaussian distribution for every muscle, and we plotted their centers (on/off area centers) in the phase planes for all trials. In the same way, we examined the distribution of on/off area in the torque plane of the ankle, knee, and hip (torque vs. torque velocity plane) for each muscle and calculated their centers. We conducted one sample t-test for coordinates (angular displacement/torque and angular velocity/torque velocity) of on/off area centers from five trials for each muscle to statistically compare on/off distribution on laterality or among participants. Significant levels of differences between five-sample data and zero value (i.e. significant distance from x or y axis) were tested using *ttest* in the statistical toolbox of Matlab (p = 0.05).

RESULTS: We calculated the center of mixed Gaussian distribution for each on/off area in the phase plane. Figure 1 shows 80 samples (from 8 subject of 5 trials, both legs) of on-area center (red) and off-area center (blue) for each muscle in the phase planes of the ankle, knee, and hip joints.

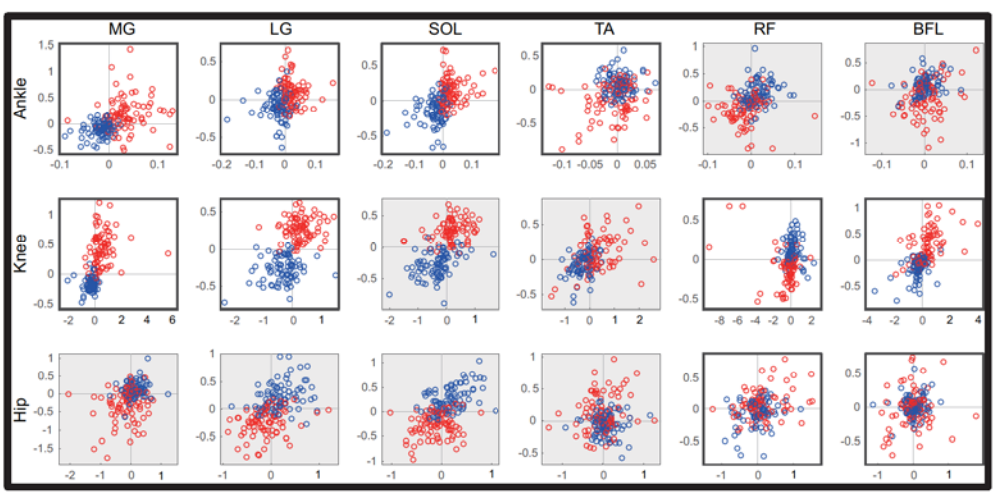

Figure 1: Distributions of on/off area centers in the phase plane.

In general, most muscles activated when the state point located in anatomically opposite area in the phase plane and deactivated when it is in the anatomical action direction. Especially, MG and LG tended to activate/deactivate when the state point located in dorsiflexion/planterflexion of the ankle and extension/flexion of the knee. RF and BFL also tended to activate in knee flexion and extension, respectively, and to deactivate vice versa. In addition, although triceps surae muscles do not directly (anatomically) actuate the hip joint, they activated and deactivated when the hip fluctuated in backward and forward, respectively. The results of one sample t-test on the five-trial data of on/off area center coordination in the phase plane were as follows: there were individual variation and laterality in the location of the state point (position, velocity, or both) to trigger phasic muscle activities.
We also obtained the center of mixed Gaussian distribution for each on/off area in the torque plane to examine the relationship between phasic muscle activation/deactivation and joint torque fluctuations as a control output. Figure 2 shows 80 samples (from 8 subject of 5 trials, both legs) of on-area center (red) and off-area center (blue) for each muscle in the torque planes of the ankle, knee, and hip.

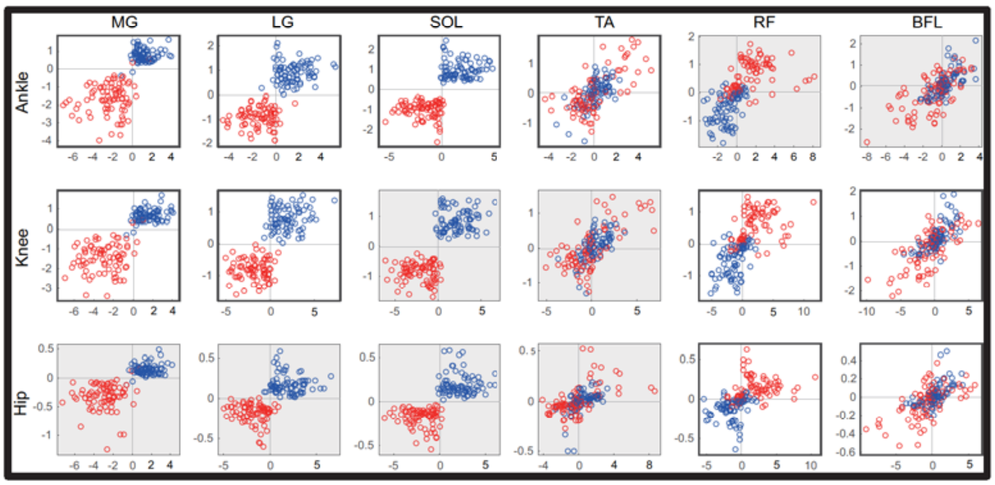

Figure 2: Distributions of on/off centers in the torque plane (torque vs. torque velocity).

The distributions of on/off area centers in the torque planes were relatively small compared with those in phase planes (Figure 2). Centers of on-area and off-area of triceps surae muscles distributed in the third and first quadrants, respectively, in the ankle and knee torque planes, indicating that their phasic activation and deactivation were associated with torque generations in anatomical action direction. In addition, centers of on-area and off-area were separated in the third and first quadrant, respectively, in the anatomically non-involving hip torque plane. Similar results were obtained for RF on/off areas. On the other hand, the on/off area centers of TA and BFL were not separated clearly. One sample t-test on the five-trial data of on/off area center coordination in the torque planes showed that such variability for TA and BFL in torque planes was mainly due to variability between participants and laterality. The results of t-test for the other muscles (triceps surae muscles and RF) statistically showed that phasic activation/deactivation of these muscles involved in torque generations in anatomical action directions.

DISCUSSION: In this study, we were able to experimentally visualize causality among joint oscillations, phasic (intermittent) muscle activities, and torque output during quiet standing. Distributions of the on/off centers revealed that each muscle activated when the state point located in anatomically opposite position and deactivated when the state point located in anatomical action direction (Figure 1). These results correspond to the hypothesis of intermittent feedback control strategy, in which control input is triggered based on the location of the state point in the phase plane. In addition, on/off centers in the torque planes showed that phasic muscle activation and deactivation were associated with joint torque generation in anatomical action direction and opposite direction, respectively (Figure 2). In particular, on/off areas of triceps surae muscles explicitly distributed over the third and first quadrant, respectively, of the ankle and knee torque planes, suggesting that anti-gravity muscles intermittently activate or deactivate in order to accurately handle the ever-present gravitational toppling torque during quiet standing. RF activation and deactivation was also associated with torque generation in anatomical action direction of the knee and hip (i.e., knee extension and flexion, and hip flexion and extension, respectively). Although RF on/off area in the hip phase plane was widely distributed, RF on/off area on the hip torque plane explicitly separated into the first and third quadrant. One of the most important results in this study was that muscle deactivation itself was also associated with the torque generation in anatomically opposite direction. Thus, the individual differences and laterality of the on/off area distribution were relatively small in the torque planes in contrast with those in the phase planes. These results indicate that the function of intermittent muscle activity is to generate joint torque precisely along with the action direction. There are three possible explanations for such on/off variability in the phase plane. One is that transfer lag of afferent feedback is individually and laterally different. Second, efferent control input via muscular and skeletal system varies individually and laterally. This laterality could be affected by the difference in the EMG electrode placement positions between legs. The last possibility is that the on/off trigger timing of phasic muscle activities (i.e., the reference value of the state point for each muscle) is modulated depending on individually or laterally different mechanical/structural body properties (such as segment length, joint viscoelasticity, or physiological cross-sectional area of muscles) so as to precisely generate joint torque in the anatomical action direction.

In this study, extracting phasic components of muscle activities allowed us to observe the direct relationship between kinematics and muscle activity during quiet standing, which has long been difficult to demonstrate because joint fluctuations are aperiodic and muscle activities are small and contain many frequency components during quiet standing without any disturbances. Our results will comprise fundamental knowledge of postural control closed-loop mechanisms and are useful for evaluating the balancing skill of athletes in future analysis. Once we have demonstrated the causality in the feedback loop during normal quiet standing with healthy adults, these results can be compared with the data of athletes or the injured population, leading to deeper understanding of the balancing skill of athletes and balance disorder mechanisms. This will indicate which muscles should be trained for better balance or rehabilitation.

CONCLUSION: We demonstrated the direct relationship between joint fluctuation, muscle activities, and torque output during quiet standing by extracting phasic components from EMG signals. In conclusion, our results suggest that phasic muscle activities occur depending on the state point location in the phase space, leading to joint actuation via torque generation along with anatomical action direction. Our results can be utilized to evaluate postural balancing skills in athletes.

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