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Analysis of musculoskeletal system responses to pertrubations during standing posture

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Abstract. The purpose of the study is to examine the muscular responses of healthy adult subjects to support surface rotations in pitch and roll planes. We used an enhanced experimental approach compared to the traditionally used methods in the previous studies by other researchers where the support surface beneath the subject's feet randomly perturbed the equilibrium. Instead of a predetermined motion of the support surface that would cause the perturbation of the subject's equilibrium, we perturbed the equilibrium by a Stewart parallel platform. Mounted on the platform, a force plate was recording the motion of the centre-of-mass projection during the experiment. This setup enabled the subjects to actively control the orientation of the parallel platform by shifting the position of their centre-of-mass during the experiment. Using polar diagrams, we show the responses of four muscle groups during the stretch and proprioceptive reflex and the muscular responses to the visual stimuli. Compared to the results of the previous studies, muscular activities during the stretch and proprioceptive reflex are more equally distributed in all directions. Based on the motion of the subjects that we recorded using the motion capture system, we determined whether the muscles were stretching or extending during the responses to the perturbations. We also show the effectiveness of the muscles to compensate the perturbations in different directions.

Keywords: posture control, balance perturbation, Stewart parallel mechanism, muscle activity

1 INTRODUCTION

The ability to move while standing on two feet strongly depends on the capability of humans to maintain the balance. The postural balance is continuously challenged by predictive and unpredictable perturbations from the environment. Simultaneously, tiredness, injuries and illnesses affect the posture by changing the states of the sensorimotor system. Humans as bipeds are inherently an unstable system that requires a continuous control of the balance and posture [19]. Postural control is a complex process that requires integration of the sensory information and execution of appropriate postural responses. To maintain upright stance, the central nervous system must coordinate motion of many muscles using sensory information provided by visual, somatosensory and vestibular systems [4]. Analysis of the standing posture can be a significant indicator of the performance for each subsystem in balance and posture control [17]. We attempt to evaluate the ability to maintain the balance and standing posture using different methods and thus to monitor the progress or deficit which may be a consequence of various injuries, exercises or illnesses.

Most of the previous studies on responses to postural perturbations investigated activities of a particular subsystem in balance and posture control [2], [3], [16]. The target was to determine the control strategies in the central nervous system, by observing the kinematical and dynamical parameters and muscle synergies during quiet and disturbed postural control [10]. A useful experimental approach to understand neural control of posture is disruption of the stable equilibrium and recording of the behavioural reactions to these perturbations. The most common method to induce such perturbations to the equilibrium is by slipping, tilting, accelerating or decelerating the support surface. Achievements of these studies provide us with some insights into multi-joint coordination and multi-sensory interaction of the motor system [9].

Nashner et al. [16] first described the muscle synergies as stereotyped muscle responses to support surface translations and rotations. They reported that the muscle that is stretched during the surface translation or rotation is not necessarily activated first, but rather the muscle that is functionally relevant to the appropriate corrective balance response. The muscle responses to surface perturbations are triggered by the somatosensory system [11]. Researches [13], [5] showed that with a continuous perturbation of the support surface, in case of periodic motion of support in an anterior-posterior

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plane, the motion of the body becomes increasingly multi-segmental as the perturbation frequency increases, yielding the impression that different postural control strategies are systematically recruited. Diener et al. [7] also examined postural control at higher frequencies of the support-surface perturbation. They reported that the angular displacement of the head is smaller than that of the pelvis, suggesting that stabilization of the head and body centre of mass may be achieved by separate strategies. Experiments [6], [8], [14] produced evidence supporting the sensitivity of both muscular and biomechanical postural responses to perturbation direction. Since it is known that joint receptors and vestibular apparatus provide directional information [18], it seems essential to characterize the proprieties of postural control system using perturbations in multiple directions.

This paper focuses on examination of the muscular responses to support surface perturbations during balance and posture control. We used a refined experimental approach compared to the methods traditionally used in the previous studies by other researchers [6], [13], [8], [15], [1] where the support surface beneath the subject's feet randomly perturbed the equilibrium and the muscular responses were recorded using EMG. Instead of a simple tilting support surface to induce disturbances of the balance as used in the previous studies, we used the Stewart parallel platform. At the top of the platform,a force plate was installed that enabled the subjects to actively control the orientation of the platform by shifting the position of their centre of mass. In fact, the elicited muscular responses of the subjects due to the balance perturbation actually corrected the induced perturbation. In contrast to the previous studies where the muscular activity had no effect on the motion of the subject and was in some sense an isometric response, our reported muscular responses result in the subject's body sway and offer a better approximation of the real life situation.

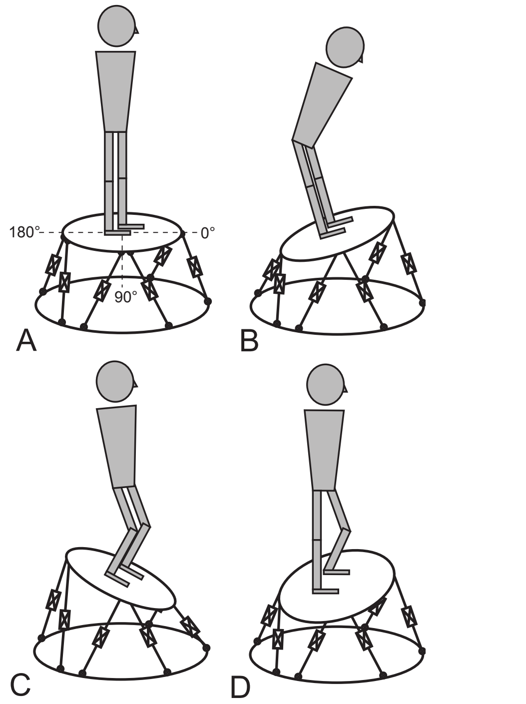

Figure 1. Situation A: initial position with no perturbation. Situation B: equilibrium correcting responses to perturbation in direction 180°. Situation C: equilibrium correcting responses to perturbation in direction 0°. Situation D: equilibrium correcting responses to perturbation in direction 90°.

2 METHODS

2.1 Participants

Ten healthy male subjects (mean age 27±3 years, weight 82±6 kg, height 175±5 cm) participated in this experiment. The subjects had no neurological or muscular disorders as verified by self report. They were all informed about the experiment protocol before signing the consent form. The procedure was approved by the local ethical committee.

2.2 Experimental setup

Disturbances to equilibrium were delivered by inclining the platform realized with the Stewart parallel platform with three degrees of freedom specifying a set of independent rotations of the support surface about arbitrary axes of the coordinate frame on the top of the platform (Fig. 1). Perturbations of the balance were specified as rotations of the support surface in the anterior-posterior (A/P) direction, media-lateral (M/L) direction or a combination of both directions. Platform rotations had a constant amplitude of 8.5°, an angular velocity of 50°/s and were randomly delivered through 16 different directions about the vertical axis. A clockwise increasing notation, as viewed from above, was used to specify rotation directions. The 0° and 180° rotation directions represent a pure A/P tilt of the platform. Pure M/L perturbations were assigned to angles of 90° and 270°. Combinations of A/P and M/L rotations were used to denote other 12 directions, each separated by 22.5°. At the top of the inclining platform, a force plate was mounted to measure the projection of the centre of mass (COM). Data on the position of COM were used to control the Stewart parallel platform in real time. EMG responses of four muscle groups were simultaneously recorded during a given experimental session. Surface EMG electrodes were placed bilaterally over tibialis anterior (TA), vastus lateralis (VAS), soleus (SOL) and paraspinalis (PARA). An optical motion-capture system was used to collect kinematic parameters using six cameras positioned around the working area. Passive markers were placed on ten anatomical landmarks of the participant's body. Markers were placed bilaterally on the shoulders, hips, knees, ankles and 5^{th} metatarsal joints.

2.3 Procedure

Before the experiment, we did the general skin preparation and placed the EMG electrodes. For each muscle group we defined the maximum voluntary contraction which was executed with an isometric resistance exercise. During the experiment session, the subjects stood on the force plate mounted on the top of the inclining platform with arms crossed on the chest. The subjects actively controlled the orientation of the platform by shifting their COM. Their feet were aligned with a predetermined distance and did not move during the experiment. A perturbation signal with a period of 15 s was added in a random direction to the actively controlled platform orientation. The subjects were instructed to maintain their balance as best as they could. Since the platform was approximately 70 cm from the ground, we enclosed it with a stage to reduce the fear of the height. The total experimental time for each session was 240 s.

2.4 Data processing

Before using the measured data for the subsequent analysis, the amplified EMG signals were full-wave rectified. We then separated the EMG signal into 16 parts from the outset of the perturbations to this declination and sorted them according to the direction of the perturbation in a clockwise notation from 0° to 360°. For each perturbation trial, the mean background value of the EMG activity for a period from 0s to 5s was subtracted from the rest of the signal. We then normalized the signals using the maximal voluntary contraction (MVC) and calculated the normalized surface of the EMG muscle activity using the trapezoidal integration (Eq. 1) on a closed time interval $(t_1,\ t_2)$ associated with the latencies of the stretch reflex (45ms – 80ms from the onset of perturbation), proprioceptive reflex (80ms – 120ms) and visual stimuli (150ms – 180ms) [12].

$$muscle\,activity = \frac{1}{MVC}100\% \int_{t_1}^{t_2} EMGdt \qquad (1)$$

For all ten sessions of the processed measurements we calculated the mean values and standard deviations of the normalized EMG areas according to the directions of the perturbation gaining the functional dependences of the normalized EMG areas with the perturbed directions. They were presented using the polar diagrams (Figs. 2 - 5). The information of the projection of the COM in the horizontal plane was obtained from the force plate. The COM data was low-pass filtered prior to the analyses, separated into 16 parts from the outset of the perturbation to its declination and sorted according to the direction of the perturbation in a clockwise notation from 0° to 360°. For each perturbation trial, the mean value was calculated when there was no perturbation representing the offset and subtracted from the maximum value of the rest of the signal. Thus, the data obtained represent the maximum deviation of the projection of the mass in the direction of the perturbation.

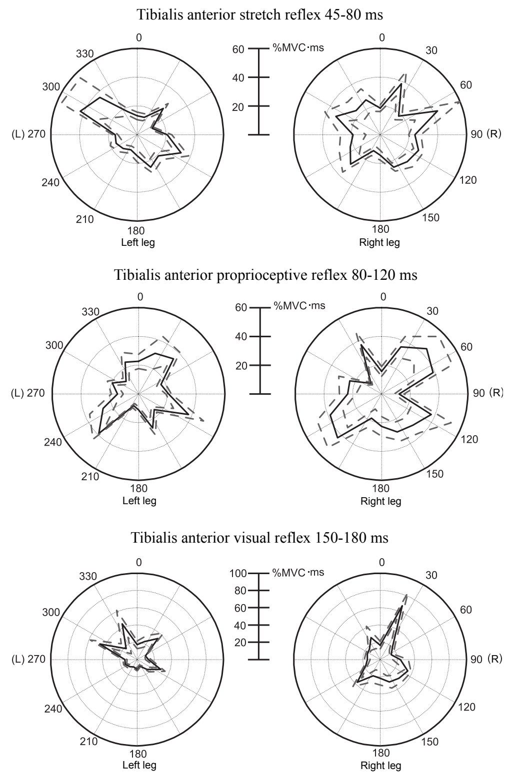

Figure 2. Polar plots of the mean area of the normalized EMG activity and standard deviation (dashed line) for the tibialis anterior muscle of ten subjects. The responses were measured for rotational perturbations in 16 different directions during stretch reflex (45 ms), proprioceptive reflex (80-120 ms) and visual stimuli time intervals (150-180 ms).

3 RESULTS

Using polar diagrams, we show the mean value and the standard deviation of the normalized EMG area of four muscle groups for the left and right leg depending on the direction of the perturbation during the stretch reflex, proprioceptive reflex and visual stimuli. Polar diagrams are also used for showing the maximum deviation of COM in perturbed direction. The responses to perturbations in multiple directions were stereotypical and direction dependant. The perturbations induced a direction-specific displacement of body segments during the first 180 ms from the onset of the stimuli. Balance corrections consisted of multi-segmental activities with latencies of 100 ms and 150 ms from the stimulus onset. Displacements of the body in the A/P directions were corrected earlier than in the M/L direction.

	Tibialis anterior %MVCms				Soleus %MVCms			
Perturbation direction	*Anterior*	*Posterior*	*Medial*	*Lateral*	*Anterior*	*Posterior*	*Medial*	*Lateral*
Stretch reflex	26	15	13	13	130	120	120	120
Proprioceptive reflex	15	22	12	12	120	170	120	120
Visual stimuli	19	20	12	12	100	160	110	110

	Paraspinalis %MVCms				Vastus lateralis %MVCms			
Perturbation direction	*Anterior*	*Posterior*	*Medial*	*Lateral*	*Anterior*	*Posterior*	*Medial*	*Lateral*
Stretch reflex	120	80	80	80	200	110	110	110
Proprioceptive reflex	80	120	80	80	180	200	110	110
Visual stimuli	80	40	80	80	200	160	110	110

Table 1. Normalized muscular activities in anteroposterior and mediolateral directions of perturbations

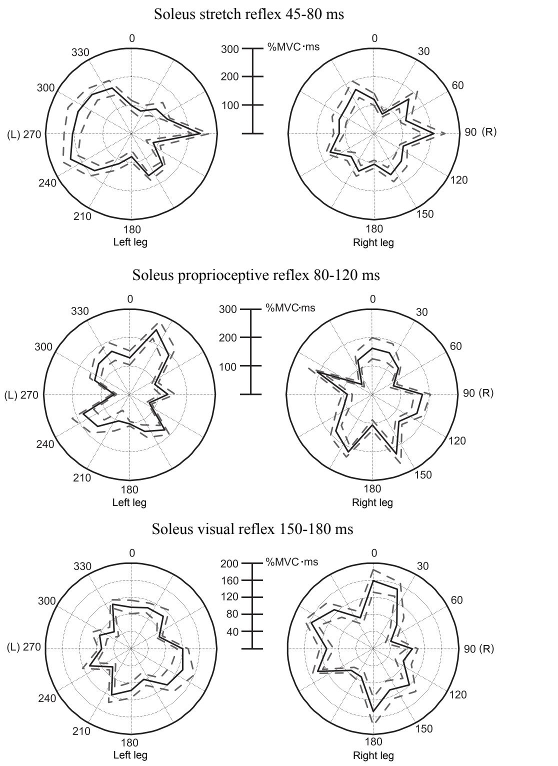

Figure 3. Polar plots for the soleus muscle. For other details refer to Fig. 2.

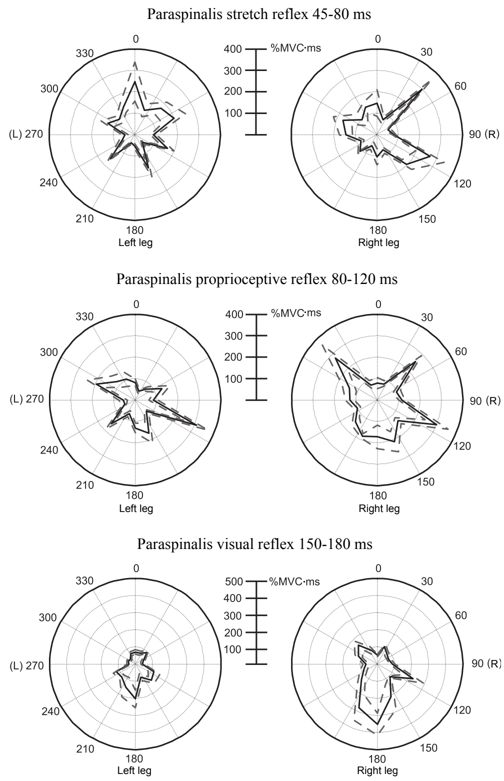

Figure 4. Polar plots for the paraspinalis muscle. For other details refer to Fig. 2.

The area of the TA muscle activity shows a constant value of 13% MVCms during each of the experiment sessions (Table. 1, Fig. 2). At the onset of stretch reflex in ca. 50 ms from the onset of the stimuli, the activity in the anterior direction is increased with a value of 26% MVCms. In the posterior direction, the activity is constant with a value of 15% MVCms. At the onset of the proprioceptive reflex during 80 – 120 ms, an increased muscle activity occurs in the posterior directions between 150° and 210°, with maximum activity oriented approximately at 180° with a value of 22% MVCms.

The area of the SOL muscle activity is more equally distributed in all directions of the perturbation (Fig. 3). The muscle activity in the M/L direction has an average value of 120% MVCms. During the stretch reflex, the muscle activity in the direction of 315° and 45° is equal for both the left and right leg with a value of 150% MVCms. In the A/P direction there is an average muscle activity with the value of 100% MVCms (Tab. 1). For the balance correcting responses at the onset of the proprioceptive reflex, an increased activity occurs in the posterior direction with a value of 150% MVCms, with the greatest activities directed in 135° for the left and 200° for the right leg with a value of 190% MVCms.

At the onset of the stretch reflex of the PARA muscle there is an increased activity with a value of 150% MVCms directed in 45° and 315° for the left and right muscle, respectively (Fig. 4). In the backward direction, the activity is decreased to 90% MVCms. During the visual stimuli, the activity is lower with a value of 70% MVCms compared to the activity at the proprioceptive reflex. There is also a reduced activity in the anterior direction with a value of 30 %MVCms.

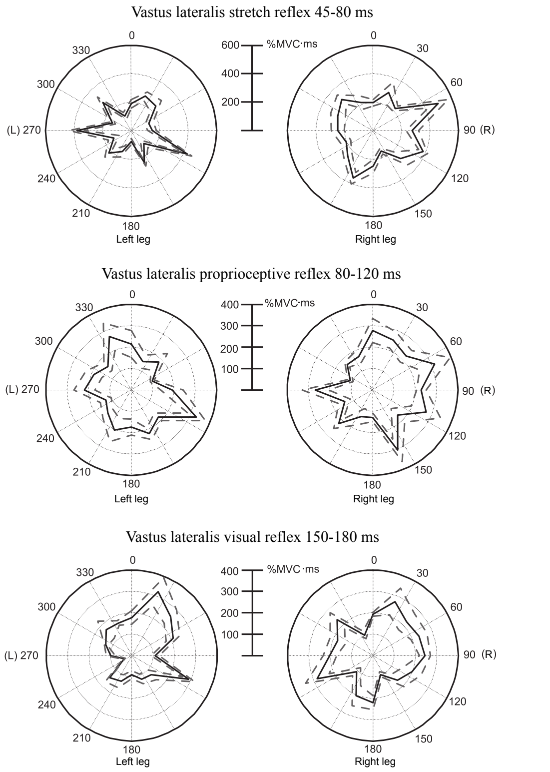

Figure 5. Polar plots for the vastus lateralis muscle. For other details refer to Fig. 2.

For the perturbation in the anterior direction, the activity of the VAS muscle during the stretch reflex reached 200% MVCms (Fig. 5). The activity for the posterior direction of the perturbation was less and reached about 110% MVCms. During the proprioceptive reflex of the muscle, the activity is increased for the posterior direction of the perturbation and has a value of 200% MVCms. For the anterior direction, it reached a value of 180% MVCms. A visual perception causes a greater activity in the anterior direction with a value of 200% MVCms and 160% MVCms in the posterior direction. The M/L direction of the perturbation causes a constant activity of the muscle for the whole time interval and for all perturbation velocities (Tab. 1). The muscle activity of the left muscle is 100% MVCms while for the right leg, the activity is 150% MVCms.

The maximum deviation of COM was observed from the onset of the perturbation until 3 s. The displacement of COM has a maximum value of 0.07 m in the M/L direction with the perturbation in the direction of 90° and 270° (Fig. 6). A minor COM displacement occurs in the A/P direction with a value of 0.03 m.

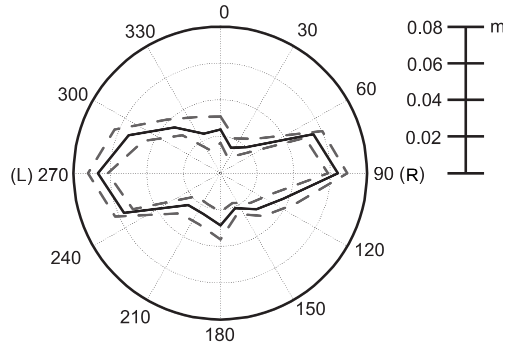

Figure 6. Maximum deviation of centre of pressure in a direction of perturbation.

4 Discussion

Previous studies investigating organization of the balance and posture control made by utilizing the multidirectional perturbation of the support surface, reported directionally sensitive activity of the postural muscles [8]. However, these studies did not separate the stretch, proprioceptive reflexes and later visual stimuli to determine how they are affected by the direction of the perturbation. Carpenter and Allum [6] reported that muscle activities in the early reaction times (stretch reflex and proprioceptive reflex) are sensitive to the direction of the perturbation. Moreover, the muscle burst due to the stretch reflex is sensitive to the direction different than the one to the proprioceprive reflex of the same muscle groups.

In our research, we used an enhanced experimental approach by upgrading the previous studies, where the muscular responses have no effect on the body movement and roughly represented the isometric contraction. We used a similar concept assuming that the subjects with their sensory-motor behavior are capable to correct induced perturbations of the balance. Compared with the results from the previous studies [6], muscular responses based on the stretch and proprioceptive reflexes are more equally distributed in all directions of the perturbation.

The muscular activities of TA, SOL, PARA and VAS are increased for all instances in the anterior direction at the latency of the stretch reflex (table 1) due to the inertia that tends to keep the rest of the body in its initial position and causing the ankle plantar flexion almost immediately. The sensory system detects changes in the body configuration and activats the muscles to prevent further rotation of the ankle. The stretch reflex of the TA muscle causes the reversal of the ankle movement, so the TA muscle works at first eccentrically to inhibit the plantar-flexion, and then concentrically to change the movement of the ankle towards the dorsal-flexion. The activity of SOL muscle at 45 ms is increased in the direction of the perturbation and stabilizes the ankle in cocontraction with the TA muscle.

While the shank movement is controlled, the rest of the body is still under the impact of inertia, leading the knee as the most unstable joint and femur to rotate, resulting in knee flexion. The activated VAS muscles stop the knee flexion and later extend the knee. The timing of the first visual stimuli is in the range of the voluntary movements from 150 ms to 180 ms. At this point, the muscular responses are essential to correct the trunk sway. In the anterior directed perturbation, the abdominal muscles are recruited first, while the posterior directed perturbation recruits the dorsal PARA muscles.

In contrast to the results of the research [6], our experiment gains explicit muscular responses in all directions of the perturbations, particularly the SOL muscle activities, This can be attributed to reciprocal coordination of the lower extremity and trunk activities.

The maximum deviation of the COM is oriented in the M/L direction (Fig. 6) due to the greater ability of maintaining the balance in the A/P direction by using the "ankle" strategy [19]. In the M/L direction, the contribution to maintain the balance is due to the "hip" strategy. The role of the "hip" strategy does not prevail because of the inability to generate a sufficiently corrective torque in the ankle.

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