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Characteristics of feedback postural control induced by unexpected surface perturbations in elite skiers

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Abstract. The purpose of this study was to examine superior feedback postural control following postural disturbance. Nine elite ski jumpers and nine control subjects were required to maintain balance without stepping following unexpected horizontal surface perturbation in a forward or backward direction. Unilateral kinematic data in the sagittal plane using a motion-capture system and surface electromyogram signals from ten trunk and leg muscles were recorded. A reduction in and reproducible peak magnitude of the center of mass (COM) velocity was shown in the athlete group compared to the control group. Cross-correlation analyses showed longer time lags at the moment of peak correlation coefficient between trunk flexor and extensor muscle activities, and the shorter time lags and higher correlations between ankle flexor and extensor muscle activities in the athlete group compared to the control group. We conclude that elite ski jumpers show superior balance performance following surface perturbations, more reciprocal patterns in agonist-antagonist pairs of proximal postural muscles and more co-contraction patterns in those of distal postural muscles during automatic postural responses compared to control individuals. This atypical strategy may be useful for effective balance recovery in an environment with a dynamically changing surface.

Keywords: postural control, ski jumpers, muscle activation pattern

1. Introduction

Production of an adequate and coordinated postural response to a postural disturbance induced by an unexpected dynamically changing environment is crucial for effective balance recovery and fall prevention in individuals of all ages. In most previous studies on postural control following a postural disturbance during standing, normal or inferior balance ability in healthy young, elderly or disabled individuals has been investigated [1-6]. In contrast, the characteristics of superior postural control required for excellent balance recovery in challenging conditions remain largely unknown [7]. The two typical muscle activation patterns, co-contraction and reciprocal patterns, have been identified in feedforward or feedback postural responses following forward-backward perturbations [2]. Co-contraction patterns may be viewed as a means of increasing the apparent stiffness of the postural joints and stabilizing the body. On the other hand, reciprocal patterns may be viewed as more efficient in moving important performance variables such as the center of mass (COM), but also less safe under poorly predictable external conditions [3]. However, the characteristics of automatic postural responses patterns among elite athletes have yet to be reported.

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The purpose of this study was therefore to investigate the characteristics of superior postural control in elite ski jumpers following surface perturbations. Ski jumping places high demands on the ability of the athlete to control posture and movement [8]. We focused on postural muscle activation patterns in agonist-antagonist pairs at major joints of the lower extremity and trunk during this postural response. We hypothesized that 1) slower and more reproducible COM velocity and 2) more reciprocal muscle activation patterns would be observed following perturbations in elite ski jumpers compared to control subjects.

2. Methods

2.1. Subjects

Nine elite skiers (athlete group: 5 men, 4 women; mean age, 19.8 ± 2.4 years) of national/international level and nine healthy adults (control group: 6 men, 3 women; mean age, 21.7 ± 1.1 years), all without any known neurological or motor disorders, participated in this study. Each subject provided written informed consent as required by the Declaration of Helsinki (1964) and the local ethics committee.

2.2. Apparatus

Unilateral kinematic data in the sagittal plane were collected using a 6-camera motion-capture system. 8 markers were used to calculate the COM, and 2 markers were attached to a movable platform (described later) to define the initiation of horizontal surface movement (time zero: t_0) in the forward-backward direction. Disposable self-adhesive electrodes were used to record unilateral surface EMGs of 10 postural muscles.

2.3. Procedures

Postural sway was induced by horizontal surface perturbation of the customized movable platform, which was adjustable in terms of movement distance and velocity. Sagittal plane balance was perturbed at random intervals by the movable platform in a forward or backward direction at a constant velocity of 39 cm/s for 150 ms (Large) or 13 cm/s for 300 ms (Small). Acceleration and deceleration time intervals were approximately 80 ms for both Large and Small perturbations. The platform moved 10 cm or 5 cm in each direction with Large or Small perturbations, respectively. The subject stood barefoot with feet side-by-side at about shoulder width and arms hanging at the sides of the body. In each trial, movement of the platform was triggered by an experimenter at random intervals from 1 to 5 s after a beep generated by a computer. Each subject was required to maintain balance without stepping, and given three practice trials prior to each task. Subjects repeated the four tasks (2 perturbations [Large and Small] × 2 directions) with 15 trials in each task. Subjects were exposed to 60 disturbances, with the trials randomized.

2.4. Data analysis

To explore time-dependent covariates in flexor and extensor muscle activity involving the major joints of the lower extremities and trunk, cross-correlation analyses were run separately for EMGs in agonist-antagonist pairs [4] over a time period from 50 ms to 200 ms after t_0 to include automatic postural response. For each trial, peak magnitude of the correlation coefficient (C-peak) and the time lag of C-peak were computed. Two-way mixed-design analysis of variance (ANOVA) was mainly used to analyze the average value and variability of the peak magnitude of COM velocity, and the C-peak and time lag of C-peak across groups. For each main factor and interaction effect, a post hoc analysis was conducted using Tukey's comparisons. Pearson's correlation coefficient between the peak of COM velocity and the time lag was analyzed in each perturbation (Large or Small). Statistical significance was set at the level of $p < 0.05$.

3. Results

Figure shows the time profiles of COM velocity in the forward-backward directions under both Large and Small perturbations for a typical subject in each group. The data represent average values and standard deviations across 15 trials in each task. A positive value on the y-axis represents COM velocity in the forward direction induced by backward perturbation. A negative value on the y-axis represents the reverse situation. Note that some increases and decreases in the time-series for COM velocity were observed in each task, during the end of the acceleration phases and start of the deceleration phases of the COM velocity in particular, in control subjects. Two-way ANOVA with factors *Group* (Athlete and control) and *Direction* (backward and forward) for Large perturbation conducted on the absolute value of the peak magnitude of COM velocity indicated a significant effect of *Group* ($F_{[1, 16]} = 23.99$, $p < 0.01$). In addition, a significant effect of *Direction* was found ($F_{[1, 16]} = 35.54$, $p < 0.01$). No significant interaction was found ($F_{[1, 16]} = 0.39$, $p > 0.1$). Two-way ANOVA with factors *Group* and *Direction* of Small perturbation conducted on the absolute value of the peak magnitude of COM velocity also indicated a significant effect of *Group* ($F_{[1, 16]} = 99.68$, $p < 0.01$). No significant effect of *Direction* ($F_{[1, 16]} = 3.29$, $p > 0.05$) or interaction ($F_{[1, 16]} = 2.58$, $p > 0.1$) was found. Two-way ANOVA with factors *Group* and *Task* (2 perturbations × 2 directions) was conducted on the coefficient of variation (CV), as standard deviation divided by the average value, with the peak magnitude of COM velocity across 15 trials indicating a significant effect of *Group* ($F_{[1, 16]} = 19.90$, $p < 0.01$).

Table shows average C-peak and time lag between flexor and extensor muscle activities in the ankle and knee joints and trunk. Note that average time lags at the moment of C-peak between flexor and extensor muscles of ankle joint were shorter in the athlete group than in the control group. Two-way ANOVA with factors *Group* and *Task* conducted on the time lag between the tibialis anterior and medial head of gastrocnemius muscles indicated a significant effect of *Group* ($F_{[1, 16]} = 4.93$, $p < 0.05$). In addition, a significant effect of *Task* was identified ($F_{[3, 48]} = 18.14$, $p < 0.01$). No significant interaction was found ($F_{[3, 48]} = 1.45$, $p > 0.1$). In contrast, average time lags at the moment of C-peak between trunk flexor and extensor muscles were longer in the athlete group than in the control group. Two-way ANOVA with factors *Group* and *Task* conducted on the time lag between rectus abdominis and erector spinae indicated a significant effect of *Group* ($F_{[1, 16]} = 6.03$, $p < 0.05$). No significant effect of *Task* or interaction were found ($F_{[3, 48]} = 1.67$, 0.10, respectively, $p > 0.1$). Average time lags between flexor and extensor muscles of the knee joint did not show any significant effect of *Group* ($F_{[1, 16]} = 2.54$, $p > 0.1$). Furthermore, two-way ANOVA with factors *Group* and *Task* conducted for C-peak of the ankle joint indicated a significant effect of *Group* ($F_{[1, 16]} = 6.14$, $p < 0.05$). No significant effect of *Task* or interaction were found ($F_{[3, 48]} = 2.23$, 1.40, respectively, $p > 0.1$). In addition, no significant effects of *Group* conducted on C-peak between flexor and extensor muscles of knee joint and trunk were found ($F_{[1, 16]} = 4.43$, 0.11, $p > 0.05$). Peak values of COM velocity showed significant positive correlations with time lags of ankle joint for the combinations of two groups and two perturbed directions, with Large or Small perturbations (r = 0.45, 0.40, respectively, $p < 0.01$). In fact, the shorter time lags of ankle joint were associated with slower COM velocity. In contrast, no significant correlation was seen between peak values of COM velocity and the lags of the hip joint for the combinations of two groups and two perturbed directions, with Large or Small perturbations (r = -0.22, -0.32, respectively, $p > 0.05$).

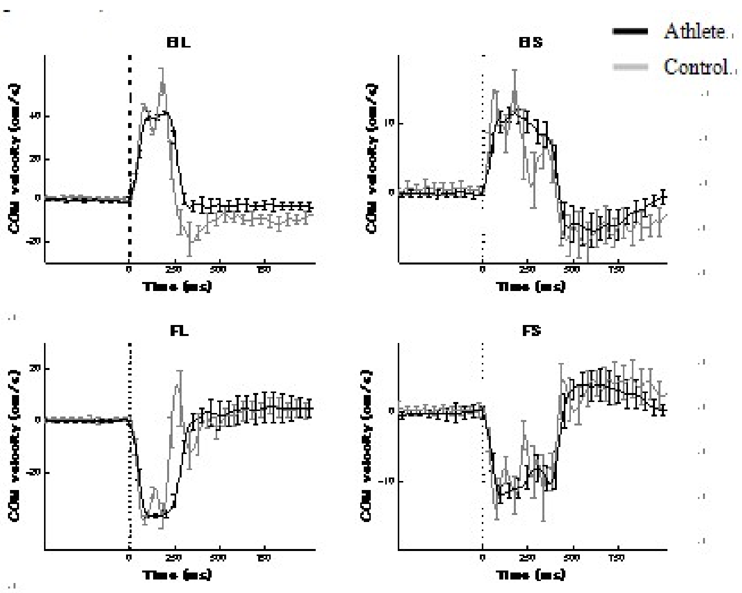

Figure: Average time profiles with standard deviation of center of mass (COM) velocity across 15 trials in a typical subject. Black and gray lines show subjects from athlete and control groups, respectively. Vertical dotted lines show initiation of perturbation (t0).

BL, backward direction of Large perturbation; BS, backward direction of Small perturbation; FL, forward direction of Large perturbation; FS, forward direction of Small perturbation. Note that some increases and decreases in the time-series for COM velocity were observed in each task, during the end of the acceleration phases and start of the deceleration phases of the COM velocity in particular, in control subjects

Table 1. Peak correlation coefficient (C-peak) and corresponding time lag between flexor and extensor muscle activities in the ankle and knee joints and trunk from 50ms to 200ms after initiation of perturbation.

		BL		BS		FL		FS		
		Athlete	Control	Athlete	Control	Athlete	Control	Athlete	Control	
Ankle (TA & GM)										
	C-peak	0.87 ± 0.02	0.87 ± 0.03	0.86 ± 0.04	0.83 ± 0.03	0.90 ± 0.04	0.86 ± 0.06	0.89 ± 0.03	0.83 ± 0.06	*
	time lag (ms)	33.7 ± 18.3	34.2 ± 12.1	11.2 ± 8.5	25.0 ± 12.0	5.7 ± 2.9	17.0 ± 14.0	7.3 ± 9.0	17.9 ± 16.2	*
Knee (RF & BF)										
	C-peak	0.80 ± 0.03	0.84 ± 0.03	0.83 ± 0.05	0.85 ± 0.04	0.84 ± 0.04	0.86 ± 0.03	0.87 ± 0.03	0.87 ± 0.03	
	time lag (ms)	26.1 ± 9.4	23.9 ± 10.4	16.4 ± 12.8	12.5 ± 7.2	22.4 ± 11.3	14.1 ± 9.0	14.4 ± 9.8	11.3 ± 8.3	
Trunk (RA & ES)										
	C-peak	0.83 ± 0.03	0.84 ± 0.03	0.84 ± 0.04	0.83 ± 0.05	0.80 ± 0.04	0.83 ± 0.04	0.82 ± 0.03	0.82 ± 0.04	
	time lag (ms)	40.3 ± 14.7	35.6 ± 14.6	30.5 ± 17.0	21.1 ± 16.3	33.3 ± 14.5	19.7 ± 7.6	30.7 ± 21.2	19.3 ± 12.3	*

Values represent average ± SD. *TA*, tibialis anterior; *GM*, medial head of gastrocnemius; *RF*, rectus femoris; *BF*, biceps femoris; *RA*, rectus abdominis; *ES*, erector spinae. Abbreviations are the same as in Figure 1. * $p < 0.05$.

4. Discussion

The current study showed better performances in terms of COM velocity in the athlete group following not only Large perturbations, but also Small perturbations, as indicated in our first hypothesis. That is, reduced peak magnitude and reproducible trajectories of COM velocity were shown in the athlete group compared to the control group. Few studies have analyzed postural performance in elite skiers and the results remain controversial. Noe and Paillard [10] reported that national-level skiers displayed postural performance inferior to that of regular skiers under static and dynamic conditions without ski boots. A platform with movable pivot and only one degree of freedom of movement was used to analyze dynamic balance [11], and skiers were instructed to maintain the platform as horizontal as possible for 25.6 s [10]. Dynamic balance according to the methods of that study would thus mainly involve ankle strategy, not whole-body postural recovery, and would require feedforward control as well as feedback control. Accordingly, we suggest that elite ski jumpers have better feedback postural control under unexpected dynamically changing conditions.

Longer time lags of C-peak between trunk flexor and extensor muscle activities were observed in the athlete group. Conversely, shorter time lags and higher correlations (C-peak) between ankle flexor and extensor muscle activities were observed in the athlete group (Table). The short time lag and high correlation between agonist-antagonist muscle activities are due to the fact that they show a pattern of approximately simultaneous contraction (co-contraction) [5]. The present results thus indicate that the flexion-extension muscles of the trunk in the athlete group showed a more reciprocal pattern of activation than the control group, supporting our second hypothesis. In particular, large fluctuations in COM velocity during the end of acceleration and at the start of the deceleration phase of COM velocity were found in the control group (Figure). In contrast, smooth trajectories of COM velocity roughly in accordance with the velocity of the movable platform were seen in the athlete group. The reciprocal patterns of proximal muscles may thus absorb inertial forces of rapid postural perturbations more easily compared to co-contraction patterns. We have shown that co-contraction patterns in feedforward postural responses occurred more frequently under unstable conditions than under stable conditions, and changed to reciprocal patterns from co-contraction patterns with practice [6]. In addition, reciprocal patterns may be viewed as more efficient in controlling important performance variables such as COM [3]. Taken together, the higher reproducibility of COM velocities across repetitive trials in the athlete group would be partly attributable to reciprocal patterns due to motor learning under challenging conditions. Strong muscle strength [12], instantaneous force [13], relevant proprioceptive organs [9] and predict postural control [16] in individual athletes would be other factors inhibiting fluctuations in COM velocity.

Interestingly, the results of this study indicate that flexion-extension muscles at the ankle joint in the athlete group activated with more of a co-contraction pattern than seen in the control group. Furthermore, we indicated for the first time the relationship between peak COM velocities and time lags in agonist-antagonist muscle pairs at the ankle joint. In fact, the stronger the co-contraction pattern at the ankle joint, the slower the peak COM velocities. We therefore suggest that elite ski jumpers reduce the rapid COM velocities through stiffness in the ankle joints, according to the co-contraction pattern at the ankle joints. This strategy of fixing distal joints rather than proximal joints following surface perturbations may illustrate a long-term effect of repetitive wearing of ski boots [10]. This is because stiff ski boots restrict ankle joint motion [14], and restriction of ankle movement is known to exert significant effects on postural control [15]. Postural control without boots in athletes such as elite gymnasts is worthy of investigation in a future study.

We conclude that elite skiers show: 1) slower and more reproducible COM velocity following horizontal surface perturbations; and 2) more reciprocal patterns in agonist-antagonist pairs of proximal postural muscles and more co-contraction patterns in agonist-antagonist pairs of distal postural muscles during automatic postural response compared to control individuals. This strategy may be useful for effective balance recovery in environments with a dynamically changing surface in the field of sports science, as well as in rehabilitation.

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