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Patterns of Lower Limb Muscle Activity in Young Boys During a One Foot Static Balance Task

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Activity patterns of four major muscles were studied in the support leg during a standard one foot balance test. Electromyographic (EMG) activity of the tibialis anterior (TA), peroneus longus (PL), gluteus medius (GM), and adductor magnus (AM) was recorded from 10 boys (aged 7–9 yr) during 30 s balance trials. Rectified, low-pass filtered EMG data, converted to percentages of maximum contractions, were used to establish muscle activation patterns. The results showed that lateral shifts in balance were primarily mediated by the ankle musculature, while the hip muscles appeared to stabilize the pelvis. Immediately prior to lateral shifts of the center of pressure (COP), the activity of each ankle muscle was similar to the activity of the following pose. The hip muscles, however, were not consistently linked to ankle activity. Thus, the control of one-legged lateral balance does not rely on fixed hip-ankle synergies.

Key words: EMG, posture, leg, balance.

Each year thousands of school children throughout the United States are recommended for physical or occupational therapy, partially on the basis of their balancing abilities. Almost every motor development test used to evaluate these children contains a one foot static balance item. This item is included in clinical assessments with the assumption that static balance is a measure of the "health" of the nervous system (Cratty, 1969). Many balance investigators assume that poor balance is the result of cerebellar dysfunction or a vestibular problem (Barsch, 1967). The possibility that poor balance may also result from peripheral problems, such as specific muscular weakness, is often overlooked.

One example of such a peripheral problem, labeled the Trendelenburg Sign (Sherrill, 1976), results from a weakness of the gluteus medius. This specific muscle weakness produces a pelvic tilt during a one foot balance task. Such an ipsilateral pelvic drop may cause a child difficulty in performing a one foot balance test. Similarly, other examples of specific weakness may exist which could contribute to a child's loss of balance. Identification of such balance problems requires an understanding of the involved muscles' actions. Since a review of the literature yielded no studies describing muscular contributions during a one foot static balance task, this study was undertaken to assess the activation of four lower limb muscles during one foot balancing.

While no studies have described muscle activation patterns during one foot balancing tasks, there are studies reporting muscle activation patterns of standing children in response to postural perturbations. Shumway-Cook and Woollacott (1985) found that 7–10 year old standing subjects responded to horizontal displacements of the support surface with fixed activation patterns of functionally related postural muscles of the lower limb. For example, in response to induced forward sway the gastrocnemius contracted and was followed by the contraction of the hamstrings. Each pattern of muscle activity displayed a fixed ratio of activity, was specific for a certain movement, and was functionally related to coordinating one kind of postural adjustment. Similar fixed muscle synergies for two-legged anterior-posterior postural control have also been described in children above the age of seven by Forssberg and Nashner (1982) and in adults (Nashner, 1977).

It seemed reasonable that fixed patterns of muscle activity might also be present in a one foot static balance test. In such a task, the primary joints of concern are the ankle and hip of the supporting leg, as lateral sway is the critical controlled variable and the knee has no lateral degrees of freedom. In previous studies of two-legged anterior-posterior balancing, platform perturbations were imposed to reveal synergies functioning to provide postural stability. In one-legged static balancing, however, subjects experience frequent shifts of weight which are accompanied by shifts in muscle activity. This situation obviated the need for imposing perturbations to study balance-related muscle activity patterns. Since the role of "coordinative structures" (Easton, 1978; Turvey, 1977) such as postural synergies is an issue of current debate in the motor control literature, the data were analyzed to discern activity patterns related to the coordination of lateral postural adjustments.

Method

Subjects

Ten boys between the ages of seven and nine (M = 8.28 years) who weighed between 29.5 and 38.6 kg (M = 35.2 kg), served as volunteer subjects. All subjects had no diagnosed disabilities and possessed normal balancing ability.

Apparatus

The platform used in this study was designed to detect lateral postural adjustments. A board (15.2 cm × 30.5 cm) was supported in the center and would tilt left or right two degrees. As a subject attempted to maintain or regain balance by applying pressure laterally, thereby moving the center of pressure (COP), the platform board would tilt. Each movement of the platform board activated electrical switches which produced a unique signal recorded on an eight channel instrumentation tape recorder (Hewlett-Packard model 3968). The electromyographic signals were amplified by Harvard Apparatus preamplifiers and differential amplifiers (Tektronix AM 502) and then recorded with the balance signal on FM tape.

Procedure

Pairs of surface electrodes (Ag/AgCl, Beckman) were placed over the gluteus medius (GM), adductor magnus (AM), tibialis anterior (TA), and peroneus longus (PL) of the right leg, in accordance with the placement sites described by Delagi, Perotto, Iazzetti, and Morrison (1975). A skin resistance of 10K was the highest accepted level while the criterion for minimum signal to noise ratio was 10 to 1.

Before the balance trial began, maximum isometric contraction of each of the monitored muscles was assessed. The subject performed the primary action of the muscle against an immovable resistance. Three maximum contractions were obtained for each of the monitored muscles.

Each balance trial began with the subject child's right foot placed in the middle of the balance platform. The subject then folded his arms with the elbows flexed and his hands tucked into his chest. The subject's left leg was touched and he was told to lift the corresponding foot, without hopping or moving around. As soon as the subject lifted his foot, a stopwatch was started. Each trial lasted for 30 s. The watch was stopped if the child placed his left foot back on the ground, if his hands were extended to gain balance or if he hopped or moved on the foot on which he was balancing. This was repeated until the child completed three trials of 30 s each. There was a two-minute break after each trial to prevent muscle fatigue, whether or not the subject balanced for the full 30 s.

Data Analysis

Following the subject's departure a hard copy of the data, rectified and low pass filtered (BAK, PAY-1, 50 ms time constant), was made using a Harvard Apparatus 305 Penwriter. A planimeter (Keuffel and Esser, 77295) was used to measure the area under the curve.

Maximum contractions were obtained to provide a fixed scale for comparisons across muscles and subjects. A one-second interval of the maximum contraction was selected for measurement, and the trial with the greatest value was then chosen to represent the maximum contraction for that muscle. The EMG signals recorded during the test trials were reduced to percentages of maximum contraction for comparative purposes.

Occasionally a subject's COP would shift back and forth very quickly, resulting in the completion of each circuit several times within a one-second time span. To avoid the dynamic interactions of such rapid movements, a one-second period of stability before a platform board shift was used as the minimum criterion for measurement. The subject was posed laterally either left or right for at least one second before a weight shift, in order for the EMG patterns to be analyzed. EMG data were studied from two time periods relative to the weight shift: a stable "pose" (of one second or longer), and a "pre-shift" (the last 100 ms before a shift of the platform board to a new pose).

To determine if there were specific patterns of EMG activity, 10 trials each of the right and left poses and pre-shifts were analyzed for each of the subjects. Each subject's individual percentages of maximum contraction (PMC) were combined into a mean PMC for each of the four designated time periods (pose left, pre-shift right, pose right, pre-shift left). At this point in the analysis, data from one subject were discarded because his level of EMG activity and muscle activation pattern were vastly different from those of the other nine subjects, suggesting a balancing strategy quite unlike any of the others.

Additionally, it became clear that for each muscle a majority of subjects employed one particular activation pattern (Major Pattern). To determine the significance of elements in each pattern, a two-way repeated measures ANOVA (positions X trials) was performed for each muscle on the PMC data from all subjects displaying the Major Pattern. Tukey's *post hoc* tests were used to determine which particular mean PMCs were different.

To clarify the relationship between the antagonist muscle pairs (PL and TA; GM and AM), PMC difference scores for these pairs of muscles were obtained.

Large differences, and variable differences across positions would indicate that the muscles were working in an antagonistic fashion. Small differences, or consistent differences across conditions, would suggest that the muscles were working in a synchronized manner. During this portion of the analysis, data from all nine remaining subjects were included. A two-way repeated measures ANOVA and *post hoc* tests were applied to group means of the difference scores for each position to determine if significant differences existed for each muscle pair.

Results

Composite averages of the PMC Major Patterns are shown in Figure 1. Levels of activity in the AM were low and did not differ across positions (Figure 1A). Activity in the GM was greater in the pose-left than in the pose-right position ($F = 5.76(1,3), p < .01$). In the pre-shift positions GM activity was similar to the preceding pose (Figure 1B). In the pose-right position the TA (Figure 1C) was more active than in the pose-left position ($F = 25.32(1,5), p < .01$). The final 100 ms of the pose-left position (pre-shift right) yielded a large increase in activity ($F = 11.70(1,5), p < .01$), compared to the preceding portion of the pose, while during the final 100 ms of the pose-right position (pre-shift left) the TA activity decreased compared to the rest of the pose ($F = 26.40(1,5), p < .01$). These changes during the pre-shift positions were both in the direction of the following pose. The PL (Figure 1D) displayed greater amounts of activity in the pose-left position compared to the pose-right position ($F = 20.12(1,6), p < .01$). In the pre-shift right position a dramatic drop in activity was seen when compared to the pose-left position ($F = 23.03(1,6), p < .01$), and the pre-shift left position displayed an activity level slightly higher than the preceding portion of the pose ($F = 8.25(1,6), p < .05$). As with the TA, these shifts were both in the direction of the following pose.

For the PL-TA difference scores (Figure 2A), the activity in each pose was similar to that in the preceding pre-shift. The pose-left score was significantly greater than the pre-shift right score ($F = 27.19(1,8), p < .01$), and the pose-right score was significantly less than the pre-shift left score ($F = 15.08(1,8), p < .01$). As was expected on the basis of the PMC activity patterns, the largest mean difference was found between the pose-left and pose-right positions ($F = 27.19(1,8), p < .01$). The basic pattern for the GM-AM difference scores was a constant value for the mean in all four positions (Figure 2B). None of the comparisons tested approached statistical significance.

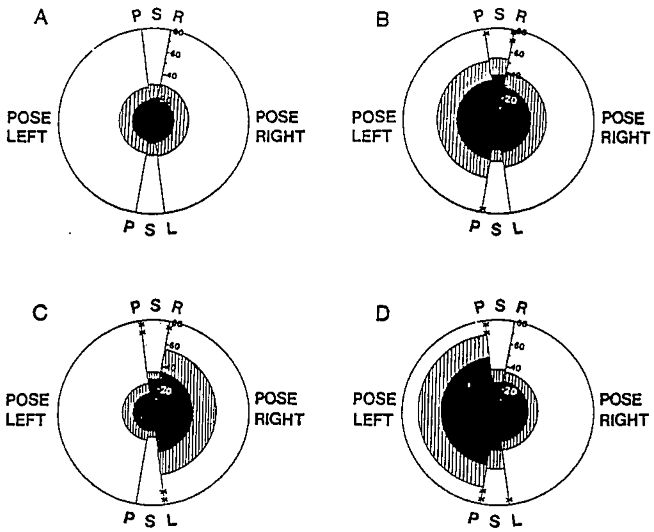

Figure 1—Major patterns of EMG activity during balancing for four muscles: a) adductor magnus, n = 5; b) gluteus medius, n = 6; c) tibialis anterior, n = 6; d) peroneus longus, n = 7. Solid area depicts percentages of maximum contraction (displayed radially); hatched area indicates one standard deviation. Regions of circles clockwise from top left represent phases of balance position: pose right, pre-shift left (PSL), pose left, and pre-shift right (PSR). Significant differences are indicated at transition lines (x = $p < .05$, xx = $p < .01$).

Discussion

These findings supported four observations with regard to activation patterns. The first of these was that the PL and TA operated as a classic agonist-antagonist muscle pair with respect to lateral ankle movements. This conclusion was strongly supported by the data (Figures 1C and 1D). When the TA was most active, the PL was least active and vice versa. Since the PL contributes to eversion at the ankle joint, while the TA contributes to inversion, anatomists have traditionally labeled these two muscles as antagonists. The present study supported this distinction.

The second conclusion, and possibly the most significant in terms of remediation programs for poor balancers, was that the level of activity in the preshift positions for the two ankle muscles was very close to the level of activity in the following pose. However, this activity level was different from the preceding portion of the pose. This can be clearly seen in Figure 1.

One explanation for this activation pattern is that during a pose the body's center of mass was located to one side of the ankle, requiring the contralateral ankle muscle to remain fairly active to prevent a loss of balance. In the pose-left position, the body's position naturally inclined the foot toward an inverted position. To resist this strong inversion tendency and to stabilize the body around the ankle, the everting PL

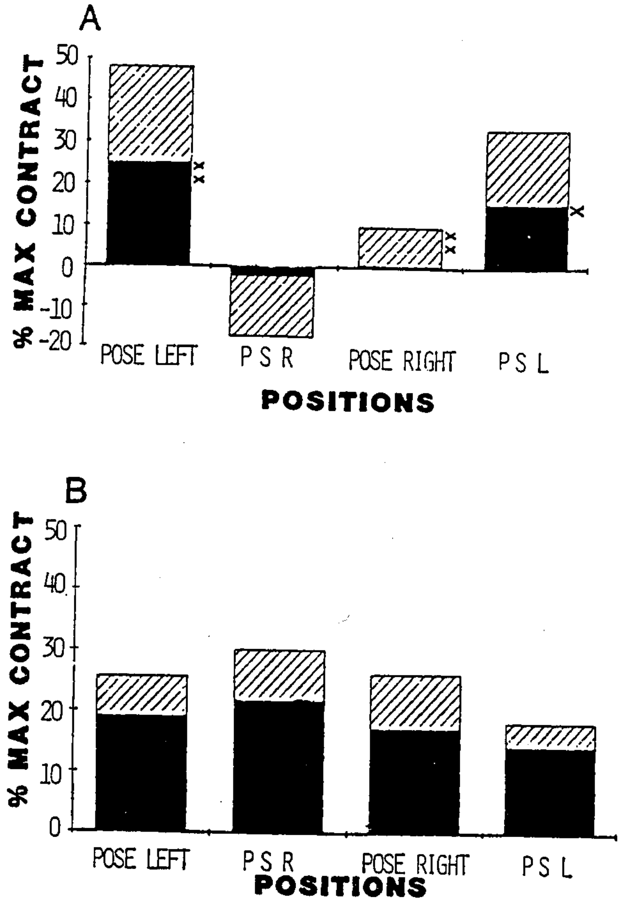

Figure 2—Percentages of maximum contraction difference scores by balance position: a) PL-TA, n = 9; b) GM-AM, n = 9. Solid area represents group mean (10 trials per subject); hatched area indicates one standard deviation. Significant differences are indicated (x = p < .05, xx = p < .01).

remained active during the pose. During the pose-right position, the foot was placed in an everted position. This resulted in the TA remaining active to resist the eversion tendency.

As a mechanical consequence of the extreme lateral position of the COP, the body's center of mass must be moving from that side. This movement would reduce the effort required of the stabilizing ankle muscles. As the center of mass would approach a position aligned vertically above the ankle, the subject would have to reposition the COP to the other side in order to slow the lateral movement of the center of mass. This rapid adjustment would be reflected in a reversal of relative muscle activation, preceding the actual shift of COP across the balance point. Thus, the two ankle muscles studied appear to contribute significantly to postural control during one-legged balancing by adjusting the COP relative to shifts in the center of mass.

The third conclusion was that the two hip muscles studied were not activated consistently relative to shifts in the COP. This was suggested by the fact that only the ankle muscles showed significant changes in accordance with the shifts of the COP. The hip muscles were not involved in weight shifts in the same manner or extent as the ankle muscles. It is likely that during this balance task, the main function of the hip musculature was to act as a stabilizing force on the pelvis, the muscles of the right side working to hold the pelvis in a horizontal position. This observation is consistent with the Trendelenberg Sign, in which weak hip musculature results in a loss of balance because of pelvic tilt. These data suggest that the contribution of the hip muscles studied was not related to lateral shifts in weight.

The final conclusion of this study was that the seemingly appropriate ankle and hip muscles only worked as a functionally related pair to a limited extent. The AM displayed an activity pattern unrelated either to changes in TA activity or to weight shifts. The GM activity pattern varied significantly in accordance with lateral poses in a manner similar to the PL. However, the GM activity failed to follow the pattern of the PL during the pre-shifts (compare Figures 1B and 1D). Instead, the pattern of GM activation during these periods was consistent with that of the TA (compare Figures 1B and 1C). This was to be expected, since the two ankle muscles work in a reciprocal manner in controlling lateral foot motion. Therefore, the point to be made is that during the relatively stable poses the GM and PL appeared to be working in a functionally related fashion, while during the pre-shifts the GM and TA may have been functioning synergistically. Thus, rather than a consistent functional linkage between pairs of muscles, in some positions the GM was paired with the TA and in other positions with the PL. Nashner and his coworkers (Nashner, 1977; Nashner & Woollacott, 1979; Nashner and Cordo, 1981) have extensively studied two-legged postural control synergies related to anterior-posterior displacement, showing hip and ankle muscles to work together as functionally related pairs. For example, Nashner (1977) found that in response to forward displacement the gastrocnemius and hamstrings were activated to pull the body back into upright stance. In response to backward displacement the tibialis anterior and quadriceps served the same purpose. The present study's results revealed only a weak functional relationship, if any, between the ankle and hip musculature specific to one-legged lateral balancing.

The most obvious explanation for this finding was suggested earlier. In a one foot balance task, the primary function of the hip muscles is the maintenance of a level pelvis. Since the point of support of the pelvis is very far to one side, shifts of weight within the width of the supporting foot are not large enough to change the basic demands on the lateral hip musculature. It is conceivable that in a lateral balance test using both legs, a bilateral pair of ankle and hip muscles would be found to be functionally related.

It must also be noted that Nashner's work has primarily described postural synergies employed in response to externally generated perturbations. The present study, however, examined self-generated shifts in balance. While this difference in experimental paradigm might be related to the presence or absence of fixed muscular synergies, there is no reason to suppose separate mechanisms to be involved. In fact, Nashner and Woollacott (1979) have argued that the reflex synergies revealed by external perturbations are identical to centrally-generated postural and locomotor patterns. Rather, the results of this study appear to be directly related to the biomechanical characteristics of the task. In a one foot balance test, the base of support is so narrow that only small lateral excursions of the center of mass are possible. Within that range of "successful" performance, an abduction torque is consistently required at the hip. Without an alternating pattern of activity between the hip antagonists, there is little chance of finding fixed bilateral ankle-hip synergies.

In summary, this study presented data on EMG activity of four muscles in the supporting leg during one foot static balancing. Since this test is frequently used to assess balance ability as well as neuromotor coordination, it is important to determine the actual function of the involved musculature. The results suggest that the PL, TA, and GM play important roles in this task. The possibility of specific weakness in these muscles should be considered in cases of poor balance performance. Although multijoint muscle synergies have been described in two-legged, anterior-posterior postural control, such synergies were not found between the ankle and hip muscles tested in this study. Rather than providing a conflicting view of postural control systems, this difference probably reflects the influence of the underlying mechanics on neuromuscular activity patterns.

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