Balance and Joint Stability: The Relative Contributions of Proprioception and Muscular Strength

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Objectives: To determine whether proprioception or muscular strength is the dominant factor in balance and joint stability and define what type of ankle rehabilitation is most effective for these purposes.

Setting: The University of North Carolina Sports Medicine Research Laboratory.

Subjects: Thirty-two healthy volunteers free of head injury, dominant leg injury, and vestibular deficits.

Design: Subjects were divided into control, strength-training, proprioceptive-training, and strength–proprioception combination training groups. Balance was assessed before and after 6-week training programs.

Measurements: Static, semidynamic, and dynamic balance were assessed.

Results: Subjects showed no improvement for static balance but improved significantly for semidynamic ($P = .038$) and dynamic ($P = .002$) balance. No significant differences were observed between groups.

Conclusions: Enhancement of proprioception and muscular strength are equally effective in promoting joint stability and balance maintenance. In addition, no 1 type of training program is superior to another for these purposes.

Key Words: ankle rehabilitation, ensemble coding, muscle spindle


Gambetta and Gray refer to balance as “the single most important component of athletic ability” because of its implicit involvement in nearly all forms of movement.\textsuperscript{1,15} Balance can be defined as a condition during which the body’s center of gravity (COG) is maintained within its base of support.\textsuperscript{2} Nashner\textsuperscript{3} concludes that balance is achieved through a compilation

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of sensory, motor, and biomechanical processes. As balance and joint stability mutually depend on sensory input from peripheral receptors, balance can be interpreted as a function of joint stability. Being a joint of the lower extremity in close proximity to the body’s base of support, the ankle plays an integral role in maintaining balance. Thus, the stability of the ankle joint is paramount when considering regulation of balance.

Joint stability is derived from a number of structures and mechanisms, both mechanical and neural, that serve to restrict joint motion to normal anatomical limits. Static structures including ligaments and joint capsules provide static restraint to excessive joint excursion, and proprioceptive mechanisms contribute further to joint stability by facilitating neuromuscular control. Proprioception is a blanket term that refers to a specialized component of tactile sensation including recognition of kinesthesia (sensation of joint movement) and of joint position sense. Proprioceptive sense is derived from a culmination of sensory input from specialized receptors in muscles (ie, muscle-spindle receptors and Golgi tendon organs), joint capsules, ligaments, and cutaneous receptors that is conveyed to the central nervous system (CNS) through afferent neural pathways. Information from these mechanoreceptors is processed to provide a neural signal designed to facilitate neuromuscular control in an effort to compensate for deviations in stance or gait. In that neuromuscular control is an important component of joint stability, the strength of the muscles acting on a joint is also a contributing factor. In addition, eccentric strength enhances joint stability by providing antagonistic resistance to joint translation. As such, a stronger muscle or muscle group has a heightened ability to promote joint stability.

Maintaining balance is a function of a number of sensory inputs to the CNS, including visual, vestibular, and somatosensory components. Postural sway is compensated for by the neuromuscular control mechanism by way of reactive neural-feedback loops between the CNS and the musculoskeletal system, as well as feed-forward mechanisms compiled from previous motor experiences. Thus, proprioception and muscular strength play essential roles in regulating balance by way of neuromuscular control. Research has substantiated the theory that injuries to the ankle joint not only result in damage to anatomical structures such as ligamentous supports, contractile units, and the joint capsule but also that they often include a deficit in proprioception because of alterations in the ability of mechanoreceptors within these structures to relay appropriate information to the CNS. In addition, balance deficits have been observed after lateral ankle sprains. Functional ankle instability can result from alterations in proprioceptive sense, allowing for increased deviation of the COG outside the base of support. Chronic symptoms including dysfunction of various types have been reported in as many as 15% to 50% of individuals who sustain acute damage to the lateral ligaments of the ankle with the most common residual symptom being functional instability.
ankle injuries are among the most common injuries in sports, particularly those that involve running and jumping,\(^{14}\) emphasis on treating, rehabilitating, and preventing these injuries is paramount in the clinical setting.

As previously stated, both proprioception and muscular strength contribute to balance and joint stability. Traditionally, rehabilitation programs after ankle injury have focused on facilitating both modalities, but little research has been conducted to determine which is more important for restoring normal function. Furthermore, research has not determined the extent to which each factor contributes to balance and joint stability. Thus, the purpose of the current study was to determine whether proprioception or muscular strength is the dominant factor in controlling balance and joint stability, while at the same time ascertaining what type of ankle rehabilitation protocol is most effective for these purposes.

### Subjects

Thirty-two physically active subjects (19 women, 13 men) 18–25 years old were recruited for the study. Subject characteristics are presented in Table 1. Subjects were solicited through posted advertisements and consisted of volunteers from the University of North Carolina at Chapel Hill student population. Before participating, subjects read and signed an informed consent form that had been approved by the university’s institutional review board.

Subjects were deemed eligible to participate in the study based on the following criteria: The ankle of the dominant leg had been free of injury for at least 6 months before testing, subjects had no history of head injury within 1 month before testing, and subjects had no known vestibular deficits. Leg dominance was defined by the leg that each subject would use to kick a ball.

### Methods

Subjects were randomly assigned to 1 of 4 groups: control (no training), proprioceptive training, strength training, and proprioception–strength combination training \((n = 8\) for each). All subjects completed a balance screening under a pretest condition. Balance assessments consisted of 3

### Table 1  Subject Characteristics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
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<tbody>
<tr>
<td>Height (cm)</td>
<td>173.13 (±10.74)</td>
<td>154.94</td>
<td>193.04</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>69.25 (±13.53)</td>
<td>48.18</td>
<td>93.18</td>
</tr>
<tr>
<td>Age (y)</td>
<td>20.84 (±1.72)</td>
<td>18</td>
<td>25</td>
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tests designed to isolate various types of balance capabilities. The order in which the tests were administered was randomized in order to eliminate any effects of fatigue that might have resulted from the testing process. After balance assessments, subjects began a 6-week training program specific to the groups to which they had been assigned. Subjects were required to report to the athletic training room 3 times per week for a total of 18 training sessions. After completing the training programs, they once again performed the balance assessments under a posttest condition.

For the purposes of clarity, it is important to discuss the different types of balance that were chosen for analysis. Static balance infers that a subject attempts to maintain the COG within a fixed, stable base of support. A relevant clinical example would be a single-leg stance on a level floor. Semidynamic balance involves the attempt to maintain the COG within a stable yet moveable base of support. An example familiar to the sports medicine and physical therapy communities is that of the biomechanical ankle platform system (BAPS) board, which is a stable, rigid platform capable of movement about a multidirectional axis. Dynamic balance infers a changing base of support. Examples include running and hopping activities during which the surface a subject is in contact with is in a state of change, requiring alterations in the strategies used to regulate balance.

**Balance Assessment**

**Static Balance**

Static balance was assessed using the NeuroCom Smart Balance Master long-forceplate system (NeuroCom International, Inc, Clackamas, Ore). This system consists of a stable, flat surface containing force transducers interfaced with a computer. Subjects performed 3 trials of a single-leg stance on the dominant leg with eyes closed and hands on hips for 10 seconds, with 1 minute of rest between trials (Figure 1). Subjects were instructed to flex the knee and hip of the uninvolved leg so that it could be maintained in a position of comfort for the duration of each trial. The force transducers monitor the subjects’ center of balance (COB). As the force that the subject exerts on the platform (ground-reaction force) is transferred outside the COB as a result of postural sway, the distance the force travels relative to the COB is calculated. By measuring the distance that the ground-reaction force travels in degrees within the specified time interval, the subject's sway velocity can be calculated: velocity = (Δ distance)/(Δ time).

**Semidynamic Balance**

Semidynamic balance was assessed using the Biodex Stability System (Biodex Medical Systems, Inc, Shirley, NY). This device consists of a rigid platform capable of movement about a multidirectional axis. Subjects
performed a single-leg stance on the dominant leg, with hands on hips and eyes closed, for 10 seconds in each of 3 trials, with a 1-minute rest between trials (Figure 2). The knee and hip of the uninvolved limb were flexed to a position of comfort. Testing was performed at level 6 on a scale of 1 to 8, with 8 being the most stable. Pilot testing before data collection for the current study indicated that subjects had considerable difficulty in completing trials during which the testing level was lower than 6 without visual stimulation. Level 6 presented a sufficient challenge to subjects' somatosensory systems while allowing for completion of trials. Data were reported as the overall stability index, representing the variance of the platform's deviance from a flat or neutral position.

Dynamic Balance

Dynamic balance was assessed using a modified version of the Bass Test of Dynamic Balance. Subjects completed a pattern through which they were required to hop and land on a series of 10 marks placed on the floor in a standardized manner (Figures 3 and 4). The direction in which the subject began the test (ie, left or right) depended on leg dominance. Subjects who were right-leg dominant initially hopped to the left, and vice versa. Landing marks consisted of 1-by-1-in pieces of athletic tape. On landing on each mark, the subject attempted to completely cover it with the metatarsal heads,
Figure 2  Semidynamic balance assessment using the Biodex Stability System (Biodex Medical Systems, Inc, Shirley, NY).

Figure 3  Dynamic balance assessment using a modified version of the Bass Test of Dynamic Balance.
Figure 4  Outline of functional pattern used for the modified version of the Bass Test of Dynamic Balance (adapted from Johnson and Nelson\textsuperscript{15}).

while at the same time maintaining balance for as long as possible with the calcaneus lifted off the ground for up to 5 seconds. Scoring was conducted as follows: Successfully covering the desired mark earned a score of 5 points; 1 point was added to the score for each second that the subject maintained balance, for up to 5 seconds. Thus, it was possible to earn a total of 10 points for each mark, with a perfect score being 100 points. Scoring deductions were arranged into 2 categories. Landing errors included failing to stop on landing on a given hop (ie, taking subsequent hops to regain balance), failing to completely cover the mark with the metatarsal heads, and touching any part of the body other than the metatarsal heads to the floor on landing. Each landing error resulted in a reduction of 5 points. Balance errors included touching any body part other than the metatarsal heads to the floor while attempting to maintain balance and moving the foot while in a balanced position. These errors each resulted in a 1-point reduction of the balance score per second that the subject displayed each error, up to 5 seconds.

Training Protocols

Each training protocol was designed to enhance specific contributions to balance and joint stability. Protocols were based on clinical procedures traditionally used in ankle rehabilitation. The strength-training group used
Theraband® free ankle weights and standing calf raises to promote muscular strength. The proprioceptive-training group used the 4-square ankle-rehabilitation program, T-band kicks, the BAPS, and a medium-density foam block to enhance proprioceptive mechanisms. The 4-square ankle-rehabilitation program requires subjects to hop in 4 standardized patterns in a design placed on the floor. T-band kicks require the subject to react to oscillating perturbations about the ankle joint. Subjects in the proprioception-training group also performed a single-leg stance on a foam block. The foam block was continually compressed because of the subject’s postural sway, thus requiring the subject to react to changes in the base of support. A ball was tossed to the subject throughout each trial to deter from visual and mental concentration, isolating vestibular and somatosensory regulation of balance. The combination training group used components of both groups to achieve improved control over balance. Detailed descriptions of the training protocols are presented in Table 2.

### Data Analysis

Data analyses were performed using the SPSS 6.1 statistical software package (SPSS, Inc, Chicago, Ill). A 4 (group) × 2 (test) repeated-measures analysis of variance (ANOVA) was used to analyze the data. Separate ANOVAs
were performed using the NeuroCom sway velocity, the Biodex stability index, and the Bass total score as the dependent variables. Statistical significance was set a priori at \( P < .05 \).

**Results**

No significant improvements were observed in subjects' abilities to maintain static balance on the NeuroCom Smart Balance Master long-forceplate system. Data for 1 subject in the proprioception–strength combination training group were excluded from analysis because they were more than 2 SDs outside of the mean sway velocity. We speculate that instrumentation error was present during testing of this subject. Subjects in all 4 groups displayed similar sway velocities for static balance from pretest to posttest (\( P > .05 \); Table 3). However, significant differences (pretest to posttest) were observed in all training groups for the ability to maintain semidynamic balance on the Biodex Stability System (\( P = .038 \)) versus the control group (Table 4). Scores improved overall, as evidenced by a decrease in the stability index, but there were no significant differences between groups. Analysis of scores from the modified version of the Bass Test of Dynamic Balance revealed significant differences (\( P = .002 \)) for all training groups between

<table>
<thead>
<tr>
<th>Group</th>
<th>Pretest</th>
<th>Posttest</th>
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<tbody>
<tr>
<td>Control</td>
<td>1.94 (±0.48)</td>
<td>2.20 (±0.63)</td>
</tr>
<tr>
<td>Strength</td>
<td>1.84 (±0.42)</td>
<td>1.79 (±0.53)</td>
</tr>
<tr>
<td>Proprioception</td>
<td>1.94 (±0.62)</td>
<td>1.88 (±0.56)</td>
</tr>
<tr>
<td>Combination</td>
<td>2.13 (±0.42)*</td>
<td>2.53 (±0.84)*</td>
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*Data excluded for 1 subject.

<table>
<thead>
<tr>
<th>Group</th>
<th>Pretest</th>
<th>Posttest*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>6.59 (±2.97)</td>
<td>6.33 (±2.42)</td>
</tr>
<tr>
<td>Strength</td>
<td>7.15 (±4.10)</td>
<td>6.15 (±2.32)</td>
</tr>
<tr>
<td>Proprioception</td>
<td>6.98 (±2.89)</td>
<td>5.30 (±2.72)</td>
</tr>
<tr>
<td>Combination</td>
<td>8.02 (±3.62)</td>
<td>7.86 (±3.62)</td>
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*\( P = .038 \).
Table 5  Bass Total Score Means—Dynamic Balance

<table>
<thead>
<tr>
<th>Group</th>
<th>Pretest</th>
<th>Posttest*</th>
</tr>
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<tbody>
<tr>
<td>Control</td>
<td>66.00 (±15.66)</td>
<td>65.75 (±15.99)</td>
</tr>
<tr>
<td>Strength</td>
<td>61.75 (±13.76)</td>
<td>67.75 (±10.11)</td>
</tr>
<tr>
<td>Proprioception</td>
<td>59.75 (±7.59)</td>
<td>69.38 (±15.75)</td>
</tr>
<tr>
<td>Combination</td>
<td>53.12 (±14.79)</td>
<td>62.75 (±9.33)</td>
</tr>
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*p = .002.

pretest and posttest versus the control group (Table 5), but again no significant differences were observed between groups.

Discussion

Balance is a key component of athletic participation. Virtually all aspects of sport require participants to maintain balance in 1 or more of its forms. It has been theorized in the literature that ankle injuries have negative effects on the ability to maintain balance. Forkin et al.\(^1\) performed balance assessments in a population with chronically unstable ankles. Subjects performed a single-leg stance on a forceplate that was perturbed medially to simulate the mechanism for an inversion ankle sprain. These authors found significant balance deficits between the involved and uninvolved limbs. Pintsaar et al.\(^3\) also claim that an important relationship exists between functional ankle stability and the ability to maintain balance. Conversely, Tropp et al.\(^5\) did not find significant differences in stabilometry readings between injured and uninjured limbs. These authors did find, however, that subjects who displayed greater postural sway were more likely to sustain subsequent ankle sprains. Pintsaar et al.\(^3\) stated that postural sway is primarily controlled at the ankle. Because injuries to the ankle are among the most common injuries in the athletic setting,\(^19\) understanding the manners in which they affect the kinetic chain is paramount in the sports medicine clinical setting.

The results of the current study revealed that specific rehabilitation protocols involving strength training, proprioceptive training, and a combination of the 2 are effective in improving subjects’ abilities to perform tasks designed to assess semidynamic and dynamic balance capabilities. However, no assumptions could be made as to which form of training was most effective in promoting joint stability and balance regulation.

No improvements were observed in subjects’ abilities to maintain static balance. The lack of significant differences between pretest and posttest and between groups likely has 2 explanations. First, static balance by
definition offers very little challenge to healthy subjects with properly functioning vestibular, visual, and somatosensory systems. Although vision was eliminated from testing procedures, the other 2 systems served to compensate for its inhibition. Furthermore, no joint perturbation was applied to which the subject was forced to react. Second, a single-leg stance might be a task common to the motor-learning banks of many subjects. It is a task that can be simulated numerous times throughout the course of a day, leading to unconscious feed-forward mechanisms that might be difficult to alter without long-term training.

Significant improvements were observed in all training groups for both semidynamic and dynamic balance from pretraining to posttraining balance assessments. Improvements were expected in the proprioceptive and combination groups, because those training protocols included activities that were similar to assessment procedures. In relation to semidynamic balance, both the proprioceptive and the combination training groups used a BAPS board. As previously stated, the use of this device is nearly identical to the function of the Biodex stability system. In relation to dynamic balance, both groups performed the 4-square ankle-rehabilitation program, which requires subjects to hop and land in a prescribed pattern for a standardized period of time. This task resembles the format of the Bass Test of Dynamic Balance. Performance of these tasks during both assessment and training increases subjects’ exposure to the test and likely leads to a motor-learning effect by which improvements could be expected.

These results imply adaptation of the CNS in response to peripheral training. Subjects likely gained familiarity with specific tasks and thus were able to alter existing motor-control programs or develop new ones to meet the demands of new balancing tasks. Whereas improvements in semidynamic and dynamic balance might be accounted for by these means in the proprioceptive and combination training groups, the strength-training group did not include elements of training that simulated assessment procedures. The strength-training group focused solely on facilitating muscular strength by performing resistance exercises. However, no significant differences were observed between training groups for semidynamic or dynamic balance. The lack of significant differences between the 3 training groups suggests that proprioception and muscular strength contribute to balance and joint stability in similar manners.

The results of the current study suggest that enhancement of proprioceptive mechanisms and of the contractile apparatus, whether individually or in combination, are equally effective in promoting joint stability and the reciprocal maintenance of balance. Despite a lack of statistically significant results, our findings have clinically significant applications for rehabilitation of neuromuscular pathologies. The lack of significant differences between groups in improvements in the ability to maintain semidynamic and dynamic balance supports the theory of ensemble coding in
relation to sensory information. By this theory, afferent signals from various peripheral receptors, including muscle spindles and Golgi tendon organs, joint capsule and ligamentous mechanoreceptors, and cutaneous receptors, are processed centrally and returned via γ-motoneurons to the muscle spindle, which is referred to as the “final common input.” The muscle spindle then creates a composite signal that is projected onto contractile fibers via α-motoneurons. This composite signal provides the information necessary to facilitate neuromuscular control.20

Muscle stiffness might also play an important role in regulating balance and joint stability. As defined by McNair et al,21 muscle stiffness is the ratio of the change in force applied to a muscle to the resultant change in length. When considering regulation of postural sway associated with static balance tasks, simple resistance to muscle lengthening (ie, muscle stiffness) might have significant effects. In the absence of perturbation, this resistance accounts for a large amount of the gravitational forces that cause the body’s center of gravity to fluctuate around its base of support.22 Muscle stiffness might also enhance neuromuscular control by reducing electromechanical delay associated with the spinal stretch reflex23 and increasing muscle-spindle sensitivity to stretch.24 A potential increase in muscle stiffness in the strength-training group could help explain the lack of significant differences among training groups, while at the same time providing further justification for the theory of ensemble coding. Resistance exercise, particularly eccentric forms of it, increases muscle stiffness.25

Although muscle stiffness was not a variable investigated in this study, subjects in the strength-training group likely increased the stiffness of the musculature surrounding the ankle joint by performing resistance exercises. As previously stated, a stiffer muscle displays higher levels of muscle-spindle sensitivity to stretch. As the “final common input” by the theory of ensemble coding, an increase in the sensitivity of the muscle spindle would potentially increase the sensitivity and efficiency of the neuromuscular control mechanism. Furthermore, because the theory of ensemble coding states that the final signal projected onto the α-motor system is a composite of signals from a variety of peripheral receptors, enhancement of any type of receptor potentially results in improvements in neuromuscular control. Thus, the improvements in balance capabilities in all of the training groups might be the result of modifications of specific receptors that contribute to the composite signal created by the muscle spindle.

Conclusions

Rehabilitation programs designed to facilitate proprioception and muscular strength, whether individually or in combination, are equally effective in promoting balance and joint stability. The implementation of simple, inexpensive strengthening techniques might suffice in lieu of more expen-
sive and involved training devices in the clinical setting when considering time constraints. More research is needed to determine the extent to which muscle stiffness affects joint stability and the maintenance of balance.

References


