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ORIGINAL RESEARCH REPORT

Prediction of Dynamic Postural Stability During Single-Leg Jump Landings by Ankle and Knee Flexibility and Strength

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Context: Dynamic postural stability is important for injury prevention, but little is known about how lower-extremity musculoskeletal characteristics (range of motion [ROM] and strength) contribute to dynamic postural stability. Knowing which modifiable physical characteristics predict dynamic postural stability can help direct rehabilitation and injury-prevention programs. ***Objective:*** To determine if trunk, hip, knee, and ankle flexibility and strength variables are significant predictors of dynamic postural stability during single-leg jump landings. ***Design:*** Cross-sectional study. ***Setting:*** Laboratory. ***Participants:*** 94 male soldiers (age 28.2 ± 6.2 y, height 176.5 ± 2.6 cm, weight 83.7 ± 26.0 kg). ***Intervention:*** None. ***Main Outcome Measures:*** Ankle-dorsiflexion and plantar-flexion ROM were assessed with a goniometer. Trunk, hip, knee, and ankle strength were assessed with an isokinetic dynamometer or handheld dynamometer. The Dynamic Postural Stability Index (DPSI) was used to quantify postural stability. Simple linear and backward stepwise-regression analyses were used to identify which physical characteristic variables were significant predictors of DPSI. ***Results:*** Simple linear-regression analysis revealed that individually, no variables were significant predictors of the DPSI. Stepwise backward-regression analysis revealed that ankle-dorsiflexion flexibility, ankle-inversion and -eversion strength, and knee-flexion and -extension strength were significant predictors of the DPSI (R^2 = .19, P = .0016, adjusted R^2 = .15). ***Conclusion:*** Ankle-dorsiflexion ROM, ankle-inversion and -eversion strength, and knee-flexion and -extension strength were identified as significant predictors of dynamic postural stability, explaining a small amount of the variance in the DPSI.

Keywords: musculoskeletal, Army, balance, lower extremity

Postural stability is the ability to maintain the body in equilibrium by keeping the center of mass within the base of support. Maintaining postural stability requires the integration of sensory information and execution of appropriate motor responses. Postural stability can be measured with static tests or dynamic tests. Static tests use a fixed, firm, unmoving base of support, while dynamic tests use movements requiring a change in position or location.[1–3] Prospective studies have demonstrated that impaired static postural stability is a risk factor for ankle and leg injuries.[4–6] However, static tests may not be the best choice for athletes, who may have higher balance ability, requiring a shift toward using dynamic postural-stability tests. The rationale for using dynamic postural-stability tests is that they are more challenging and similar to athletic activity. Furthermore, there is a poor relationship between static and dynamic postural stability, indicating they may measure different aspects of postural stability.[7]

There are 2 ways of testing dynamic postural stability. One way is when the base of support stays in 1 place and the subject moves within that base of support, an example being the Star Excursion Balance Test (SEBT). The SEBT requires the subject to maintain balance while completing purposeful single-leg movements without changing the location of the base of support, and it has been found to be predictive of lower-extremity injury.[8] Another way to test dynamic postural stability is by having subjects change the location of the base of support and maintain their postural stability, as with single-leg jump landings.[3] Postural stability is then quantified with the Dynamic Postural Stability Index (DPSI), which measures the variability in ground-reaction forces (GRFs) on landing. The use of single-leg jump landings is advantageous because they place additional demands on the neuromuscular system, closely replicate athletic tasks, and are a common lower-extremity-injury mechanism, although the ability of the DPSI to predict lower-extremity injury has not been established.[3,9–11]

After an injury, it is recommended that rehabilitation programs focus on restoring ankle flexibility and

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joint range of motion, as well as lower-extremity and trunk strength, before athletes return to play in attempt to avoid reinjury. Previous research has demonstrated that intervention programs incorporating flexibility and strength training of the lower extremity and trunk are capable of improving dynamic postural stability,[12,13] as well as reducing injury in athletes.[14–16] When looking at dynamic tasks, adequate lower-extremity strength is required for performance of single-leg jump landings.[17] Those studies, however, did not determine which trunk, hip, knee, and ankle motion and strength variables predict dynamic postural-stability performance. Previously, we demonstrated that peak GRFs, hip-flexion angle at the time of foot contact, and hip-abduction peak torque predicted DPSI.[18] For this study we wanted to include lower-extremity predictor variables that could be targeted with strength and range-of-motion interventions. Based on previous literature, we believed it would be important to include ankle range of motion because ankle dorsiflexion is a risk factor for ankle sprains,[6,19] and improving ankle range of motion and strength decreased risk of falling in older adults.[20] In addition, knee-extensor strength has been found to be a significant predictor of static and dynamic balance in the elderly.[21] Literature on trunk strength indicates that trunk-extensor-muscle performance (strength and endurance) is associated with static-balance scores in elderly individuals with limited mobility,[22] and that core-strengthening programs improve static postural stability,[23] as well as dynamic postural stability measured with the SEBT.[12,24]

We believe that it is important to simultaneously investigate physical characteristics as predictors of dynamic postural stability measured with the DPSI after single-leg jump landings in our population of interest (young active male military). The purpose of this study was to identify which trunk and lower-extremity variables are significant predictors of dynamic postural stability during single-leg jump landings. We hypothesized that trunk, hip, knee, and ankle strength, as well as ankle range of motion, would be identified as significant predictors of dynamic postural stability. Identifying these physical characteristics will help direct clinicians in choosing appropriate interventions to improve strength and range of motion in areas contributing to dynamic postural stability.

Methods

Design

This was a cross-sectional study. Subjects' ankle range of motion, lower-extremity and trunk strength, and dynamic postural stability were collected. Testing was performed over 2 days separated by approximately 1 week as dictated by the protocol for a larger ongoing study. Only the dominant-limb data will be presented herein. Limb dominance was defined as the leg used to kick a ball maximally.

Participants

Ninety-four male subjects (age 28.2 ± 6.2 y, height 176.5 ± 2.6 cm, and weight 83.7 ± 26.0 kg) were recruited from the Army 101st Airborne Division (Air Assault) to participate in this study. Subjects had an average of 4.5 ± 3.4 years (range 1–12) of active service, and were 18 to 45 years old with no history of concussion or mild head injury in the previous year; no musculoskeletal pathologies to the upper, lower, or back regions in the past 3 months; and no history of neurological or balance disorders. All subjects were cleared for active duty, without any prescribed duty restrictions. This study was part of an ongoing project focusing on injury prevention and performance optimization in the 101st Airborne Division (Air Assault). Human-subject-protection approvals were obtained from the institutional review boards of the University of Pittsburgh and the Dwight D. Eisenhower Army Medical Center.

Procedures

Active dorsiflexion and plantar flexion were measured with the knee bent as described by Norkin and White.[25] A total of 3 measurements were taken for each test and averaged for data analyses. A standard goniometer was used to measure ankle angle of motion (Saunders Group, Chaska, MN).

Strength of the trunk, hips, and knees was assessed using the Biodex Multi-Joint System 3 Pro (Biodex Medical Systems, Inc, Shirley, NY). Subjects were given verbal instructions, stabilized according to the manufacturer's guidelines, and provided practice trials (3 repetitions at 50% effort and 3 repetitions at maximal effort) to ensure familiarity with the strength-testing procedures. They were provided a 1-minute rest period between practice trials and test trials to prevent fatigue. Subjects performed 5 reciprocal concentric isokinetic test trials at 60°/s for trunk flexion/extension and knee flexion/extension. They were instructed to complete the 5 repetitions as hard and as fast as they could, but actual time to completion varied among subjects depending on their effort and ability. These methods for measuring isokinetic strength at the knee have ICCs ranging from .93 to .98.[26] Unpublished data from our laboratory demonstrate ICCs of .92 to .98 for the trunk measurements. Isometric hip-abduction strength was tested in the side-lying, hip-neutral position on the Biodex. Subjects completed three 5-second hip-abduction isometric contractions. These methods have ICCs of .64 to .85.[27] Ankle strength was assessed with a handheld dynamometer (Lafayette Instrument Co, Lafayette, IN). Ankle testing was completed with a handheld dynamometer, as opposed to the Biodex, due to limited ability of the ankle attachment to stabilize the foot and lower leg, limited ability to perform motion in the plane of motion of the ankle joint, and lack of availability of ankle attachments at multiple remote locations. Testing was performed in a seated position based on traditional manual muscle-strength-testing hand placement. Three trials were performed for each movement and averaged for analyses. Similar methods using a handheld dynamometer have reported ICCs of .74 to .84.[28]

Dynamic postural stability was assessed with a force plate (Kistler 9286A, Amherst, NY) at a sampling frequency of 1200 Hz during a single-leg jump landing and was using single-leg jump landings in the anterior direction (Figure 1). Our methods were adapted from Wikstrom et al[3] and Sell et al[7] and have an ICC of .86. The single-leg jump-landing task used in this study normalized the jump distance according to body height. Subjects were positioned 40% of their body height away from the edge of a force plate, and a 30-cm hurdle was placed at the midpoint between the starting position and the force plate. Jumps were normalized to height rather than distance to minimize equipment needed at the remote testing site, as well as other remote sites where the same procedures were planned to be used. Subjects were instructed to jump over the hurdle in the anterior direction from 2 feet, landing on the force plate with the test leg. They were asked to stabilize as quickly as possible, place their hands on their hips, and remain balanced for 10 seconds while looking forward. A total of 3 successful trials were collected and averaged for analyses. Subjects were provided a minimum of 3 practice trials to become familiar with the single-leg jump-landing task. Trials were discarded and repeated if subjects failed to jump over or came in contact with the hurdle, the hopped on the test leg after landing, the nontest leg touched down on the force plate or the ground surrounding the force plate, or they removed hands from their hips for longer than 5 seconds. A 1-minute rest period was provided between trials to prevent fatigue.

For all strength measures performed on the Biodex Multi-Joint System 3 Pro, the average peak torque (Nm) of the 5 repetitions was normalized to body mass in kilograms (% body weight). For strength measurements performed with handheld dynamometer, the subject performed three 5-second maximal isometric contractions against the dynamometer measured in kilograms, which were averaged for analyses and normalized to body weight in kilograms (% body weight). For all of the flexibility variables, the average of 3 trials was used for analyses. To quantify dynamic postural stability, force-plate data were passed through an amplifier and analog-to-digital board (DT3010, Digital Translation, Marlboro, MA) and stored on a personal computer. A custom MATLAB (v7.0.4, Natick, MA) script was used to process the GRF data for calculating the DPSI. GRF data were passed through a zero-lag fourth-order low-pass Butterworth filter with a frequency cutoff of 20 Hz. The description of calculation of the DPSI has been published elsewhere.[3] While multiple DPSI calculations are available, we chose this equation to be consistent across multiple studies being completed by our research group, including a reliability study of our methods. Briefly, the DPSI is a composite of the anteroposterior, mediolateral, and vertical GRFs. The first 3 seconds after initial contact was used to calculate the DPSI. Initial contact was defined as the instant the vertical GRF exceeded 5% body weight.

Figure 1 — Anterior single-leg jump landing.

Statistical Analysis

The dependent variable was the DPSI score, and the independent variables were ankle range of motion and the lower-extremity strength variables. Means and standard deviations were calculated for each variable. The variables and residuals were assessed for normality using the Shapiro-Wilk test ($\alpha = .05$), histograms, scatter plots, and Q-Q plots. For the regression analysis, the variables were assessed for homoscedasticity using the Breusch-Pagan test (a = .05) and multicollinearity using the variance-inflation-factor (VIF) method (VIF < 10).

To determine the relationship between the DPSI and the independent variables, Pearson product–moment correlations were computed. Simple linear-regression analysis was performed to determine individual predictors of dynamic postural stability. To find the best combination of physical characteristics that predict dynamic postural stability, backward stepwise regression was used. The independent variables were allowed to enter (probability = .10) and removed (probability = .20) at every step to identify the final regression model. This method demonstrated which variables were the most predictive of DPSI performance. The level of statistical significance was set at .05 a priori for all analyses. All statistical analyses were performed with STATA 11 (StataCorp LP, College Station, TX).

Results

The means and standard deviations for all variables are presented in Table 1. The Shapiro-Wilk test found that all variables were normally distributed ($P > .05$). All histograms and residual scatter plots supported the normality assumption, as well. The Breusch-Pagan test supported homoscedasticity of the variables ($\chi^2 = 0.71$, $P = .40$). VIF analyses supported no multicollinearity being present (VIF <10).

All of the range-of-motion and strength variables had little correlation (rho < 0.25) with the DPSI score.[29] Furthermore, the results of simple linear regression between each variable and DPSI score showed that, individually, none of the variables were significant predictors. No 1 variable alone was able to explain the variance in the DPSI score. The backward stepwise-regression results are displayed in Table 2. This regression model identified ankle-dorsiflexion range of motion, ankle-inversion/eversion strength, and knee-flexion/extension strength as important predictors of the DPSI ($R^2 = .19$, $P = .0016$). Ankle-plantar-flexion range of motion, hip-abduction strength, and torso-flexion/extension strength were removed from the model. The adjusted R^2 for this model was .15, indicating that approximately 15% of the variance in the DPSI score was explained by ankle-dorsiflexion range of motion, ankle-inversion/eversion strength, and knee-flexion/extension strength.

Table 1 Dependent and Independent Variables, N = 94

Variable	Mean ± SD	Minimum	Maximum
Dynamic Postural Stability Index	0.38 ± 0.05	0.24	0.49
Range of motion			
ankle dorsiflexion (°)	17.22 ± 7.26	1.33	34.33
ankle plantar flexion (°)	51.38 ± 8.26	35.67	78.00
Strength			
trunk flexion (% bodyweight)	197.87 ± 46.28	73.60	307.69
trunk extension (% bodyweight)	335.95 ± 85.34	163.00	557.74
hip abduction (% bodyweight)	162.50 ± 33.65	76.17	262.65
knee flexion (% bodyweight)	114.71 ± 23.72	56.41	175.64
knee extension (% bodyweight)	227.91 ± 40.46	104.87	317.91
ankle inversion (% bodyweight)	32.71 ± 9.19	12.13	52.80
ankle eversion (% bodyweight)	27.11 ± 6.07	8.20	43.40

Table 2 Stepwise-Regression Model Predicting Dynamic Postural Stability

Source	SS	*df*	MS
Model	0.0363	5	0.0073
Residual	0.1501	88	0.0017
Total	0.1865	93	0.002
Variable	**Coefficient**	***t***	***P***
Ankle-dorsiflexion range of motion (°)	–.0097	–1.63	.108
Ankle-inversion strength (kg)	–.0017	–2.69	.009
Ankle-eversion strength (kg)	.0030	3.19	.002
Knee-flexion strength (% body weight)	–.0006	–2.32	.023
Knee-extension strength (% body weight)	.0004	–2.69	.004
Constant	.3399	11.03	.000

Note: Based on 94 observations. $F_{5,88} = 4.26$, probability > $F = .0016$, $R^2 = .19$, adjusted $R^2 = .15$.

Discussion

The purpose of this study was to determine if lower-extremity range of motion and trunk and lower-extremity strength variables were important predictors of dynamic postural stability during single-leg jump landings. The final model included ankle-dorsiflexion range of motion, ankle-inversion/eversion strength, and knee-flexion/extension strength as significant predictors of dynamic postural stability, but not ankle-plantar-flexion, trunk, or hip strength. The variables included in the final model are supported by previous literature, which has found ankle dorsiflexion to be important for balance and demonstrated a significant relationship between greater knee and ankle strength and higher dynamic postural stability in the elderly.[20,21,30]

It is interesting to note that, individually, each independent variable failed to predict dynamic postural stability, but the combination of variables identified by the final model explains a small amount of the variance in the DPSI score when considered in combination. No single measure from the current data set predicts dynamic postural stability, but there may be a single measure not captured in this study. This suggests that multiple variables work together to contribute to dynamic postural stability and that there is not a singular physical characteristic that will predict performance. Another reason we may have found that this specific group of physical characteristics predicts DPSI score, but not any single characteristic, is that we are studying healthy, active individuals in the military without any current injury or major strength or range-of-motion deficits. Furthermore, we do not expect our population of male military personnel to have poor postural stability. This is in contrast to other literature that has studied injured or elderly populations. In those groups, 1 individual strength or range-of-motion variable that is impaired may have a greater effect on dynamic postural stability.

To further explain the variables included in the final model, we think that since the muscles of the ankle and knee were found to be important in predicting DPSI score, but not the more proximal muscle groups of the trunk and hip, our study suggests that perhaps this distal musculature is most important in stabilizing the lower extremity on single-leg landing from a jump. Theoretically, we think more distal lower-extremity characteristics may predict DPSI performance because of their relationship with dissipating GRFs and stabilizing lower-extremity joints on landing. Ankle-dorsiflexion range of motion, but not plantar flexion, was found to be a predictor of the DPSI score. This is likely because adequate dorsiflexion range of motion is essential for dissipating GRFs during landing tasks from various heights. Soft landings (less GRF) used greater range of motion than stiff landings (higher GRF).[31] Because of how GRFs are used in calculation of the DPSI score, landing with a softer landing (decreased vertical GRF) can occur with a lower (better) DPSI score.[3] To incorporate strength into this explanation, previous research has found that, during drop-landing tasks, greater eccentric work was performed by the ankle and knee musculature during soft landings than with hard landings.[31] During single-leg jump landings, the lower-extremity musculature functions to decelerate and stabilize the body's center of mass.[32] Furthermore, we think that increased strength at the knee and ankle was found to be an important predictor because it contributes to increased muscle stiffness. Increased muscle stiffness increases proprioceptor sensitivity to stretch and reduces the electromechanical delay from the muscle-spindle stretch reflex, adding stability to the joint.[33,34] Strength of the muscles on both sides of the ankle and knee joints will help stabilize each of these joints when landing. If the joints are more stable on landing, perhaps that is why dynamic postural stability is better. With this particular task, the knee and ankle musculature have been found to be the most important, rather than the more proximal musculature.

In the current study, hip-abduction, trunk-flexion, and trunk-extension strength were not significant predictors of dynamic postural stability. We thought that hip and trunk strength would be predictors of the DPSI because they would help stabilize the lower extremity proximally by controlling knee and ankle position. Several studies have investigated the effect of core-strengthening programs on postural-stability performance. When comparing our study with this literature it is important to note that while those studies used training programs targeting the muscles measured in our study, they did not directly measure strength of the trunk musculature. Dynamic balance did improve in some studies, but we do not know the baseline trunk strength of the subjects or if their trunk strength improved after training. Some research suggests that core strengthening increases postural stability in subjects with low back pain and in sedentary individuals.[23,35,36] It is possible that trunk strength is not a significant predictor of dynamic postural stability in this population because they had adequate trunk strength, were not experiencing low back pain, and were physically active.

Studies looking at the effect of core-muscle training on dynamic balance using the SEBT have found that core-stabilization exercises, but not traditional core-strengthening exercises, improve dynamic balance.[24] Another study that included core-strengthening exercises, lower-extremity strengthening, and agility exercises reported increases in SEBT performance after training.[12] In contrast, other work did not find that a core-strength-training program that included exercises for the trunk flexors, trunk extensors and hip extensors improved SEBT performance.[37] These varying results indicate that the type of training program chosen to strengthen the core is important and that performance is likely related to multiple factors rather than just strength alone. All of these studies used the SEBT, which is different from the task in our study. Subjects performing the SEBT stand in 1 place on 1 leg while reaching in different directions with the other leg. The test does not measure stabilization after landing from a jump. Because of the different physical requirements of the tasks, single-leg jump landings and the SEBT are likely measuring different components of dynamic postural stability. Our study suggests that these different tasks have different physical requirements that predict performance.

Our study design and methods have several limitations. Only healthy adult male soldiers were included in this study; therefore, our results cannot be generalized to women or injured populations. Because there are potential differences in strength, ankle range of motion, and DPSI scores in women and injured groups, the relationship among these variables in those groups should be studied. Our study population were healthy men, so it is possible that in individuals with decreased strength or postural stability, or injury, there may be a stronger relationship found. In addition, there may be flexibility and strength variables important to dynamic postural stability that were not assessed in this study. We did not give specific instructions for jumping over the hurdle beyond jumping with 2 feet and landing on 1. It is likely that subjects used various movement patterns to jump over the hurdle and land on the force plate. Future research should explore the relationship between kinematic variables and dynamic postural stability during single-leg jump landings. The strategies used during the jump and during the landing may explain additional variance in the DPSI score.

Jump landings are a common mechanism of injury in athletics and are commonly used in the laboratory setting to assess dynamic postural stability. Identifying physical characteristics that predict dynamic-postural-stability performance has clinical implication for injury-prevention and rehabilitation-training programs. The findings of our study indicate that ankle-dorsiflexion range of motion, ankle strength, and knee strength predict performance on the DPSI score after an anterior single-leg jump landing. Even though their contribution may be small in a healthy male military population, making small improvements can be important, since the subjects are not impaired at baseline. Physical training programs for performance in individuals who require dynamic postural stability when executing single-leg jumps in the anterior direction should include exercises to improve ankle dorsiflexion and strengthening for ankle inversion/eversion, as well as knee flexion/extension. This model could also potentially be incorporated into rehabilitation. Once the specific impairments and deficits of the patient have been addressed, these physical characteristics could be included to improve performance before discharge from therapy.

Conclusions

The results indicate that ankle-dorsiflexion flexibility, ankle-inversion/eversion strength, and knee-flexion/extension strength are significant predictors of dynamic postural stability during single-leg jump landings. These results are clinically relevant, as clinicians should incorporate these flexibility and strength variables into injury-prevention and rehabilitation-training programs in attempt to mitigate lower-extremity injuries. Some of the variables that are predictive of dynamic postural stability are also proposed risk factors of injury but have not definitively been shown to reduce injury risk. Furthermore, there are likely additional variables that significantly predict dynamic postural stability during single-leg jump landings, particularly kinematic variables, that should be considered when developing intervention programs. Future research should continue to explore variables that are significant predictors of dynamic postural stability during single-leg jump landings, as well as in patients with known pathologies.

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