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Single-Legged Hop and Single-Legged Squat Balance Performance in Recreational Athletes With a History of Concussion

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Context: Researchers have suggested that balance deficiencies may linger during functional activities after concussion recovery.

Objective: To determine whether participants with a history of concussion demonstrated dynamic balance deficits as compared with control participants during single-legged hops and single-legged squats.

Design: Cross-sectional study.

Setting: Laboratory.

Patients or Other Participants: A total of 15 previously concussed participants (6 men, 9 women; age = 19.7 ± 0.9 years, height = 169.2 ± 9.4 cm, mass = 66.0 ± 12.8 kg, median time since concussion = 126 days [range = 28–432 days]) were matched with 15 control participants (6 men, 9 women; age = 19.7 ± 1.6 years, height = 172.3 ± 10.8 cm, mass = 71.0 ± 10.4 kg).

Intervention(s): During single-legged hops, participants jumped off a 30-cm box placed at 50% of their height behind a force plate, landed on a single limb, and attempted to achieve a stable position as quickly as possible. Participants performed single-legged squats while standing on a force plate.

Main Outcome Measure(s): Time to stabilization (TTS; time for the normalized ground reaction force to stabilize after landing) was calculated during the single-legged hop, and center-of-pressure path and speed were calculated during single-legged squats. Groups were compared using analysis of covariance, controlling for average days since concussion.

Results: The concussion group demonstrated a longer TTS than the control group during the single-legged hop on the nondominant leg (mean difference = 0.35 seconds [95% confidence interval = 0.04, 0.64]; $F_{2,27} = 5.69$, $P = .02$). No TTS differences were observed for the dominant leg ($F_{2,27} = 0.64$, $P = .43$). No group differences were present for the single-legged squat on either leg ($P \geq .11$).

Conclusions: Dynamic balance-control deficits after concussion may contribute to an increased musculoskeletal injury risk. Given our findings, we suggest that neuromuscular deficits currently not assessed after concussion may linger. Time to stabilization is a clinically applicable measure that has been used to distinguish patients with various pathologic conditions, such as chronic ankle instability and anterior cruciate ligament reconstruction, from healthy control participants. Whereas the single-legged squat may not sufficiently challenge balance control, future study of the more dynamic single-legged hop is needed to determine its potential diagnostic and prognostic value after concussion.

Key Words: time to stabilization, mild traumatic brain injury, functional movement, recovery

Key Points

- Time to stabilization after a single-legged hop may distinguish individuals with a history of concussion from healthy control participants.
- Balance characteristics during the single-legged squat were not different between groups.
- Clinicians should consider incorporating more dynamic-balance assessments after concussion, although additional research is needed to determine their prognostic value.

Static-balance deficits after concussion have been well described[1,2] and are most commonly assessed using the Balance Error Scoring System.[3] Patients with balance deficits measured using the Balance Error Scoring System often recover within several days of injury.[4,5] More recently, movement deficits after concussion have been described during dynamic tasks, such as gait.[6] Unlike static-balance deficits, dynamic-movement deficits have been observed beyond recovery according to traditional concussion-battery assessments.[7,8] The consequences of these lingering dynamic-balance deficits are not clear. An increased musculoskeletal injury risk after return to play postconcussion has been reported by several authors.[9–12] Although only preliminary associations between dynamic movement and an increased musculoskeletal injury risk have been established,[13] researchers[6] have postulated that impaired dynamic balance may reflect diminished neuromuscular control. In a highly dynamic sport environment, even small neuromuscular-control deficits could increase the risk of musculoskeletal injury.

Beyond gait assessments, subtle motor-control deficits after concussion have been described during dynamic-movement tasks, such as jumping and cutting.[14–16] Increased lower extremity joint stiffness,[15] potentially unsafe joint loading,[16] and reaction-time differences have been reported in concussed as compared with nonconcussed (control) individuals.[14] These deficits may contribute to an increased musculoskeletal injury risk[6] and may influence long-term joint health.[17] More work is needed to determine how postconcussion movement deficits contribute to musculoskeletal injury, but preliminary data[13] suggested an association between worsening dual-task (gait with a concurrent cognitive task) walking speed and an increased musculoskeletal injury risk in the year after concussion.

Given the growing evidence for dynamic-balance deficits during a simple motor task, such as gait, understanding how balance is affected by more challenging and novel motor tasks may further inform concussion recovery. The single-legged hop requires individuals to jump from a predetermined height, land on a single limb, and achieve a stable position as quickly as possible.[18] This task recreates a common athletic movement: landing from a jump in a stable manner to initiate another movement, such as a jump or cut. Although the single-legged hop is not followed by a jump or cut, balance performance in this task may better reflect the dynamic balance required for sport participation. Single-legged squats are a dynamic extension of the traditional single-legged–stance static-balance assessment that is common after concussion. Adding movement to the single-legged stance may increase the task novelty and improve its diagnostic capacity.[19] Therefore, the purpose of our study was to determine whether dynamic-balance deficits were present during the single-legged hop or the single-legged squat between individuals with a history of concussion and a matched control group. To our knowledge, single-legged hop and single-legged squat dynamic balance have never been studied in the context of concussion. Given the balance deficits reported during other dynamic assessments, we hypothesized that individuals with a history of concussion would take longer to stabilize after a single-legged hop and display worse postural control during the single-legged squat than matched control individuals.

METHODS

Participants

A convenience sample of 30 college-aged recreational athletes (no varsity intercollegiate athletes were included) was recruited and separated into 2 groups of 15 participants: (1) concussion group (median time since concussion = 126 days [range = 28–432 days]) and (2) control group with no recent concussions matched to each injured participant on the basis of sex, age (±1 year), height (±5%), and mass (±10%). All volunteers self-reported completing moderate to intense physical activity for >30 consecutive minutes ≥3 times per week. Volunteers were excluded if they self-reported attention-deficit/hyperactivity disorder, seizure disorder, lower extremity injury resulting in ≥3 days missed from physical activity within the 6 months before the study, any history of lower extremity or low back surgery, concussion requiring hospital admittance, any concussion symptoms at the time of the study, or a history of >3 concussions. Participants in the concussion group must have sustained a concussion diagnosed by a medical professional within the 1.5 years before the study, whereas participants in the matched control group must have been without a diagnosed concussion for ≥3 years. All participants provided written informed consent, and the study was approved by The University of North Carolina at Chapel Hill Institutional Review Board.

Data Collection

Kinetic data and the center of pressure (COP) were sampled at 1200 Hz from 2 force plates (Bertec Corp, Columbus, OH) embedded in the laboratory floor. For the single-legged hop, participants were outfitted with a single retroreflective marker over the superior sacrum. A Vicon Motion Capture System (Centennial, CO) recording at 120 Hz tracked the sacral marker position during the single-legged squat for calculation of squat displacement (depth) and speed.

Single-Legged Hop. Participants stood atop a 30-cm box placed at a horizontal distance equal to 50% of their height behind a force plate. With both hands on their hips, they jumped off the box with both feet, and landed on a single limb. Participants were instructed to achieve a stable position as quickly as possible upon landing. Trials were discarded and repeated if the participant touched down with the opposite foot or if any portion of the stance foot left the force plate after ground contact. The total trial time was 10 seconds, with participants holding their best single-legged posture for as much of the trial as possible. They performed 5 single-legged hop trials on each limb in random order.

Single-Legged Squat. Participants were instructed to stand on a single limb with their toes facing forward. They were positioned with the non–weight-bearing limb flexed to 90° at the knee and approximately 75° at the hip, their hands on their hips, and their head and eyes facing forward. Participants flexed their weight-bearing knee into a squat position to maximum comfort and returned to the upright posture. They performed 5 single-legged squat trials on each limb. Each trial consisted of 5 sequential squat repetitions completed without pause at a self-selected pace.

Data Analysis

A fourth-order, low-pass Butterworth filter with a cutoff frequency of 10 Hz was applied to all kinematic data. For the single-legged hop, kinetic data were filtered using a second-order, low-pass Butterworth filter with a cutoff frequency of 12.53 Hz.[20] For single-legged squat COP, kinetic data were filtered using a fourth-order, low-pass Butterworth filter with a cutoff frequency of 14 Hz.[19] Several commonly reported balance measures were calcu-

Table 1. Dependent Variable Definitions

Task	Variable	Definition
Single-legged hop	Time to stabilization	Time until resultant ground reaction force fell below mean range of variation plus 3 SDs[9]
Single-legged squat	Center-of-pressure path	Total path of the center of pressure (cm)
	Center-of-pressure speed	Total path of the center of pressure divided by trial time (cm/s)
	Center-of-pressure velocity	Center-of-pressure displacement divided by time in both the sagittal and frontal planes (cm/s)
	Sacral displacement	Maximum range of motion of the Sacral marker in the transverse plane (cm)
	Sacral speed	Maximum range of motion of the Sacral marker in the transverse plane divided by trial time (cm/s)
	Normalized center-of-pressure path	Total path of the center of pressure (cm) normalized to participant height (cm)

lated during the single-legged squat and are defined in Table 1.

Time to stabilization (TTS) was calculated as the total time participants took to establish stable balance on their landing limb after the single-legged hop. The methods for measuring TTS have been described in detail elsewhere.[18] Using a custom MATLAB script (The MathWorks, Natick, MA), we calculated normalized (to body weight) resultant ground reaction force during the last second of each trial, when participants were believed to have established stable balance on their landing limb, by squaring each time-series value of the anterior-posterior and medial-lateral ground reaction forces, summing the values, and taking the square root of the sum.[21,22] The group mean and standard deviation of the control group only were calculated to determine the resultant ground reaction force range of variation. Three standard deviations were added to the mean range of variation, and this value was multiplied by each participant's body weight to calculate a normalized reference value for each individual in both groups. This normalized reference value represented the standardized resultant vertical ground reaction force associated with stable balance for each participant. Using a custom LabVIEW program (National Instruments, Austin, TX), we fit the entire resultant ground reaction force from the trial with an unbounded third-order polynomial. *Time to stabilization* was defined as the time when the unbounded third-order–polynomial resultant ground reaction force fit curve fell below the normalized reference value.

Statistical Analysis

Data were averaged across all trials for a given limb, and these average values were used for all statistical analyses. The *dominant leg* was defined as the self-reported limb used to kick a soccer ball for maximum distance. Dependent variables were calculated separately for the dominant and nondominant legs and were analyzed in SAS (version 9.4; SAS Institute, Cary, NC) using between-participants analysis of covariance. We covaried for the number of days between the last concussion and the testing session in all statistical models. The number of days postinjury for each concussion-group participant was subtracted from the group mean days since concussion (177 days). Control-group participants were assigned a value of zero.[14] This created a value representing mean-centered days since concussion, which was used as a covariate in all statistical models. An a priori α level of .05 was established.

RESULTS

We observed no between-groups differences in participant characteristics. Median days since concussion in the concussion group was 126 (range = 28–432). One participant in the control group reported a history of 2 concussions, the most recent of which was 1103 days (>3 years) before testing. No other control-group participants reported a history of concussion. Group characteristics and between-groups comparisons are shown in Table 2.

Single-Legged Hop. Time to stabilization on the dominant leg did not differ between the concussion (2.04 seconds; 95% confidence interval [CI] = 1.65, 2.43 seconds) and control (1.84 seconds; 95% CI = 1.49, 2.19 seconds) groups ($F_{2,27} = 0.64$, $P = .43$), but the concussed group (1.90 seconds; 95% CI = 1.68, 2.12 seconds) took longer to stabilize than the control group (1.55 seconds; 95% CI = 1.33, 1.77 seconds) during nondominant leg TTS (mean difference = 0.35 seconds; 95% CI = 0.04, 0.64 seconds; $F_{2,27} = 5.69$, $P = .02$). The TTS values are presented in the Figure.

Single-Legged Squat. No differences were observed for any of the outcomes measured during the single-legged squat for the dominant ($P \geq .11$) or nondominant ($P \geq .21$) leg. All descriptive statistics and statistical comparisons for the single-legged squat are provided in Table 3.

DISCUSSION

Numerous researchers[23–25] have suggested that dynamic-balance deficits during gait may persist beyond the return to play after concussion. These deficits may contribute to an increased musculoskeletal injury risk after concussion,[9–12] but more study of the dynamic aspects of movement is needed. Our findings indicated that TTS after a single-legged hop may distinguish individuals with a history of concussion from healthy control participants. However, we observed no between-groups balance differences for the single-legged squat.

Time-to-stabilization deficits have been identified in individuals with chronic ankle instability[18,26] or recent anterior cruciate ligament injury[27] and in female athletes at an average of 2.5 years after anterior cruciate ligament reconstruction.[22] Although seemingly small, our observed difference of approximately 0.35 seconds was similar to previously reported[22,26] group differences between individ-

Table 2. Between-Groups Comparisons of Participant Characteristics

Characteristic	Group		P Value
	Concussion (n = 15)	Control (n = 15)[a]	
	Mean ± SD		
Age, y	19.7 ± 0.9	19.7 ± 1.6	.89
Height, cm	169.2 ± 9.4	172.3 ± 10.8	.41
Mass, kg	66.0 ± 12.8)	71.0 ± 10.4	.25
	No. (%)		
Sex			
Male	6 (40)	6 (40)	NA
Female	9 (60)	9 (60)	NA
	Median (Range)		
Days since concussion	126 (28–432)	1103[b]	NA
Total concussions, No.	1 (1–3)	0 (0–2)[b]	NA

Abbreviation: NA, not applicable.

[a] Control-group participants were matched to concussion-group participants based on sex, age (±1 year), height (±5%), and mass (±10%).

[b] One control-group participant had experienced 2 concussions, with the most recent concussion occurring 1103 days before testing. No other control-group participants had a history of concussion.

uals with and those without chronic ankle instability or anterior cruciate ligament reconstruction. Furthermore, TTS measures can be used to accurately discriminate between individuals with and those without chronic ankle instability.[26] Therefore, TTS has clinical utility in identifying individuals who may be at risk for ankle injuries before or during athletic participation. Targeted injury-risk mitigation programs can be designed to strengthen the ankle joint and increase proprioception with the intention of limiting acute and chronic ankle injuries. Further research into TTS after concussion is important to determine whether it may have similar clinical applicability.

We did not find any group differences in COP characteristics during the single-legged squat. This task may not have challenged the postural-control system sufficiently to demonstrate between-groups differences in our study because the injured group was tested an average of 177 days after concussion. Future investigators should consider using acute postconcussion testing and adding a cognitive component to the single-legged squat, given that dynamic-balance deficits after concussion appeared to be more pronounced under dual-task conditions.[28] Dynamic dual-task assessments in a research setting may provide an increased challenge for the postural-control system that better reflects true sport demands.[19]

Although concussion does not damage the peripheral somatosensory organs or muscle tissue as an ankle or knee sprain does, it may affect central processing of peripheral somatosensory information. Researchers have suggested that cortical excitability decreases[29] and motor-evoked potential latency increases after concussion.[30] If somatosensory information is not processed quickly or accurately by the brain, motor output could be slowed or perturbed, leading to aberrant movement patterns during gait and dynamic movement in sport. Powers et al[29] proposed that concussed individuals may recruit fewer muscle fibers

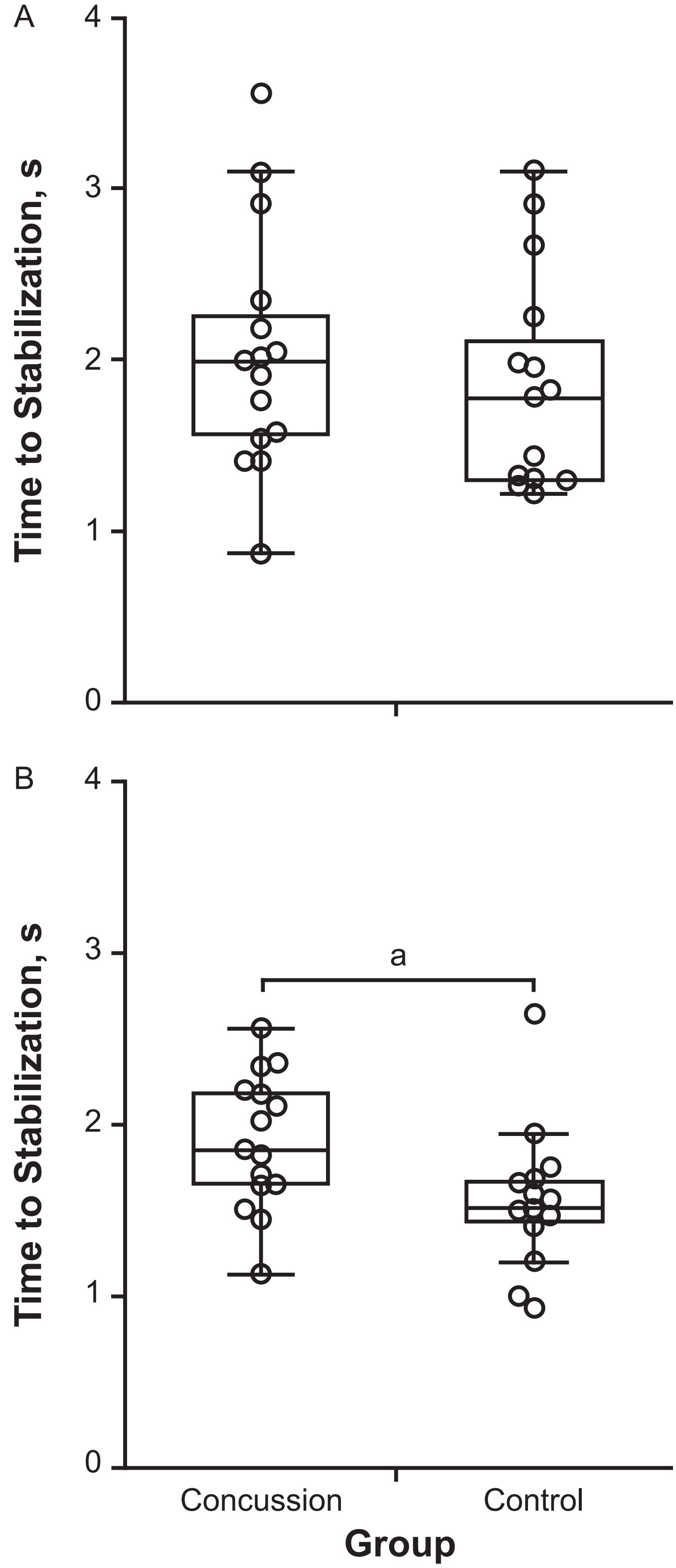

Figure. Time to stabilization during the single-legged hop for both groups: A, on the dominant leg, and B, on the nondominant leg. [a] Indicates a between-groups difference ($F_{2,27} = 5.69$, $P = .02$).

during a maximum contraction than matched control participants. Voluntary muscle activation is strongly related to strength.[31] Therefore, concussed individuals may have a reduced ability to efficiently and quickly process somatosensory information and may struggle to appropriately

Table 3. Single-Legged Squat Outcomes (Mean [95% Confidence Interval])

Outcome	Group		*F* Value	*P* Value
	Concussion	Control		
Dominant leg				
Center-of-pressure path, cm	85.6 (77.0, 94.2)	76.6 (68.0, 85.1)	2.34	.14
Center-of-pressure speed, cm/s	12.2 (10.9, 13.4)	11.9 (10.6, 13.2)	0.09	.77
Sagittal-plane velocity, cm/s	1.3 (1.1, 1.5)	1.4 (1.2, 1.6)	0.32	.58
Frontal-plane velocity, cm/s	0.7 (0.6, 0.7)	0.7 (0.6, 0.8)	0.03	.87
Sacral displacement, cm	23.5 (21.5, 25.5)	23.0 (21.0, 25.0)	0.13	.72
Sacral speed, cm/s	3.5 (3.0, 4.0)	3.6 (3.1, 4.1)	0.10	.76
Normalized center-of-pressure path	0.51 (0.45, 0.56)	0.45 (0.39, 0.50)	2.77	.11
Nondominant leg				
Center-of-pressure path, cm	83.6 (75.3, 91.9)	77.8 (69.5, 86.2)	1.01	.33
Center-of-pressure speed, cm/s	12.3 (10.9, 13.8)	12.0 (10.6, 13.5)	0.08	.78
Sagittal-plane velocity, cm/s	1.4 (1.1, 1.7)	1.3 (1.1, 1.6)	0.17	.69
Frontal-plane velocity, cm/s	0.7 (0.6, 0.8)	0.6 (0.5, 0.7)	0.06	.81
Sacral displacement, cm	22.8 (20.6, 25.0)	22.5 (20.4, 24.7)	0.03	.87
Sacral speed, cm/s	3.6 (3.0, 4.2)	3.5 (3.0, 4.1)	0.06	.81
Normalized center-of-pressure path	0.50 (0.45, 0.54)	0.45 (0.40, 0.50)	1.63	.21

respond to external stimuli with a powerful muscle contraction. In a highly dynamic environment, such as sport, even minor central-processing deficiencies or limited muscle recruitment could increase the musculoskeletal injury risk.

Whereas static balance is commonly assessed after a suspected concussion and throughout recovery, dynamic-balance assessments are not as common. Time to stabilization may allow for a more comprehensive assessment of the postural-control system in environments that more closely mimic those the athlete will experience during sport participation. Based on our observed TTS deficits, we suggest that lingering neuromuscular-control deficits may persist beyond the time when athletes traditionally are cleared to return to play. We are the first to explore TTS in individuals with a history of concussion and believe our findings underscore the need for further longitudinal studies in this area, especially because we observed no between-groups differences during the single-legged squat. An understanding of how dynamic-balance outcomes, such as TTS, are affected acutely after concussion may benefit clinical practice. Understanding the recovery of dynamic balance may result in more comprehensive and safer return-to-play testing and criteria, potentially negating undesirable consequences, such as an increased musculoskeletal injury risk.

Our study had several limitations. We observed wide variability in the time between concussion and the testing session, which could have skewed our results. We controlled for this variability in our statistical analyses, but our relatively small sample size may have minimized our ability to find larger between-groups differences. Some of our measures may have been affected by preexisting conditions, such as chronic ankle instability.[18,26] Whereas our criteria were designed to exclude participants with musculoskeletal, surgical, or central nervous system conditions that could affect outcomes, participants may have had conditions that we were unaware of at the time of testing. Our findings in this sample should be confirmed in more prospective, larger-scale investigations. Also, we studied recreational athletes. Their involvement in specific sports varied, and in many cases, our participants reported playing multiple sports. Differences in sports training, experience, and collision-sports history could have influenced the dependent variables we measured. Inferring any such influences would be speculative given the lack of empirical data supporting such statements. Sport-specific cohorts should be investigated, and tasks that are specific to movements occurring more frequently in individual sports should be assessed. Examples include anticipated and unanticipated cutting, jumping for maximal vertical height or horizontal distance, and reacting to visual or auditory stimuli while cutting or jumping.

Individuals with a history of concussion took longer to stabilize during a single-legged hop task on their nondominant legs. Given the preliminary nature of our work, the clinical utility of our findings is unclear. Researchers should develop methods that allow them to assess these variables acutely after injury and identify how dynamic balance recovers after concussion. Understanding the recovery of dynamic balance in relation to more traditional concussion-assessment measures may greatly enhance the care afforded to individuals who sustain a brain injury. Beyond dynamic-balance assessment, examining other outcomes, such as joint kinetics, stiffness, reaction time, and muscle activation, may provide important insights into neuromuscular deficits postconcussion.

CONCLUSIONS

Static balance is commonly assessed after concussion, and deficits have been described using static assessments. However, during sport participation, the neuromuscular system is challenged further, as evidenced by postconcussion balance-control deficits in gait that linger well beyond the recovery of static balance. In addition, the musculoskeletal injury risk is increased after concussion, but the underlying mechanisms for this increased risk are unknown. The observed nondominant-leg TTS deficits in a recently concussed cohort as compared with matched control individuals may provide evidence for neuromuscular deficits that are not currently addressed after concussion. Clinicians should consider incorporating more dynamic-balance assessments after concussion, although additional research is needed to determine their prognostic value.

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