Lower Extremity Stiffness Changes after Concussion in Collegiate Football Players

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ABSTRACT

DUBOSE, D. F., D. C. HERMAN, D. L. JONES, S. M. TILLMAN, J. R. CLUGSTON, A. PASS, J. A. HERNANDEZ, T. VASILOPOULOS, M. B. HORODYSKI, and T. L. CHMIELEWSKI. Lower Extremity Stiffness Changes after Concussion in Collegiate Football Players. *Med. Sci. Sports Exerc.*, Vol. 49, No. 1, pp. 167–172, 2017. **Purpose**: Recent research indicates that a concussion increases the risk of musculoskeletal injury. Neuromuscular changes after concussion might contribute to the increased risk of injury. Many studies have examined gait postconcussion, but few studies have examined more demanding tasks. This study compared changes in stiffness across the lower extremity, a measure of neuromuscular function, during a jump-landing task in athletes with a concussion (CONC) to uninjured athletes (UNINJ). **Methods**: Division I football players (13 CONC and 26 UNINJ) were tested pre- and postseason. A motion capture system recorded subjects jumping on one limb from a 25.4-cm step onto a force plate. Hip, knee, and ankle joint stiffness were calculated from initial contact to peak joint flexion using the regression line slopes of the joint moment versus the joint angle plots. Leg stiffness was (peak vertical ground reaction force [PVGRF]/lower extremity vertical displacement) from initial contact to peak vertical ground reaction force. All stiffness values were normalized to body weight. Values from both limbs were averaged. General linear models compared group (CONC, UNINJ) differences in the changes of pre- and postseason stiffness values. **Results**: Average time from concussion to postseason testing was 49.9 d. The CONC group showed an increase in hip stiffness ($P = 0.03$), a decrease in knee ($P = 0.03$) and leg stiffness ($P = 0.03$), but no change in ankle stiffness ($P = 0.65$) from pre- to postseason. **Conclusion**: Lower extremity stiffness is altered after concussion, which could contribute to an increased risk of lower extremity injury. These data provide further evidence of altered neuromuscular function after concussion. **Key Words:** NEUROMUSCULAR FUNCTION, JUMP LANDING, BIOMECHANICS, SPORTS-RELATED CONCUSSION

Sports-related concussions are a public health concern with up to 3.8 million concussions reported in the United States annually (19). Athletes with concussion are typically allowed to return to sports participation when they demonstrate normal neurological, neurocognitive, and balance evaluations; are asymptomatic at rest; and remain asymptomatic throughout a stepwise increase in physical activity (24). Even if return-to-sport criteria are met, postconcussion impairments may remain and increase the risk for musculoskeletal injury (17). Within the first year of returning to sport after concussion, athletes are up to 2.5 times more likely to sustain a lower extremity or ligamentous injury than uninjured teammates (4,21,27). In addition, retired National Football League athletes with a history of concussion had an increased risk of musculoskeletal injuries during their career than athletes without a history of concussion and risk increased with the number of concussions (30). At this time, it is unknown what impairments contribute to an increased musculoskeletal injury risk after concussion, which limits the ability to modify postconcussion rehabilitation or return-to-sport guidelines.

Unresolved neuromuscular impairments potentially underlie an increase in risk for musculoskeletal injury postconcussion (17,21). Researchers have found neurophysiological changes in the primary motor cortex beyond the time of return-to-sport from concussion, including decreased electrophysiological responses, decreased metabolic activity, and increased intracortical inhibition (6,11,16). Subclinical changes in the motor cortex could alter muscle recruitment, which in turn would affect behavioral aspects of neuromuscular function, such as movement patterns. Indeed, reduced gait velocity, reduced range of motion at the knee, and altered power generation at the hip and ankle during running have been

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identified postconcussion (20,38). In individuals without concussion, alterations in kinematic (hip, knee, and ankle range of motion) and kinetic (quadriceps activation and peak vertical ground reaction force [PVGRF]) aspects of movement patterns have been shown to increase risk for lower extremity injury (2,7,18). The link between injury risk after concussion and neuromuscular impairments may be elucidated by improving our understanding of changes in kinetic and kinematic aspects of movement patterns in athletes with a concussion.

Lower extremity stiffness, either too much or too little, is an aspect of movement that is hypothesized to be linked with lower extremity injury (5). The term stiffness is part of Hooke's law, which states that the force required to extend or compress a spring by a distance is proportional to that distance. Stiffness is computed by modeling the whole body as a mass and spring (5). It describes the ability of body segments to resist displacement after the application of vertical ground reaction forces or moments and also considers the moment–angle relationship (13,33). Stiffness can be regulated by muscular recruitment (14,15). Our pilot data, in athletes postconcussion, demonstrated quadriceps weakness and decreased time to PVGRF during a single-leg jump, which could decrease stiffness across the lower extremity (12,13).To date, the effect of concussion on neuromuscular function, particularly stiffness across the lower extremity, during a jumping task has not been characterized.

Therefore, the purpose of this study was to compare pre- to postseason changes in stiffness across the lower extremity during a jumping-landing task in athletes with or without a history of a recent concussion. It was hypothesized that 1) stiffness across the lower extremity would be similar between athletes with or without concussion at preseason testing, and 2) athletes with concussion would demonstrate a pre- to postseason decrease in stiffness across the lower extremity compared with athletes without concussion. These data can provide additional evidence of neuromuscular changes after concussion.

METHODS

Participants. The study participants were 39 Division I collegiate male football players from the same university, who participated in pre- to postseason musculoskeletal screenings during the competitive seasons in 2007–2011. This study was designed as an observational cohort study, where the main exposure of interest was concussion (yes, no) sustained by subjects, and the main outcomes of interest were leg, hip, knee, and ankle stiffness. One cohort consisted of 13 football players who had sustained a concussion (CONC), and the other cohort consisted of 26 uninjured (UNINJ) players with no history of concussion identified from electronic medical records maintained by athletic trainers. To control for confounding variables, each CONC subject was matched to two UNINJ subjects by age (±1 yr), position played, and competitive season (±1 season). All CONC subjects sustained their first reported concussion as defined by the Zurich Consensus Statement on Concussion in Sport and were diagnosed by a fellowship-trained primary care sports medicine physician, up to 90 d before postseason test session (25). If a subject sustained more than one concussion, only the first concussion was considered. All CONC subjects had been cleared to return to play before postseason testing. Certified athletic trainers verified that all subjects were free from significant lower extremity injury (any injury that limited participation in practice or competition) at the time of each testing session. Written informed consent was obtained from all subjects, and the local institutional review board approved the study.

Instrumentation. Kinematic data were sampled at 120 Hz using a 12-camera motion capture system (Motion Analysis Corporation, Santa Rosa, CA). A manufacturer-recommended calibration was performed before testing. A force platform (AMTI, Watertown, MA) was embedded into the floor, and force data were sampled at 1200 Hz and time synchronized with the motion capture system.

Procedures. Before performing the jump-landing task, a physical therapist placed reflective markers bilaterally on the acromion processes, the lateral aspects of iliac crests, the greater trochanters, the lateral and medial femoral condyles, the tibial tuberosities, the lateral and medial malleoli of the ankle, the posterior aspect of the heel, and the lateral aspect of the first and fifth metatarsal heads. An additional marker was placed on the sacrum midway between the posterior superior iliac spines. Markers used solely for segment tracking were placed on the thigh, centered approximately 10 cm above the proximal pole of the patella, and on the shank medial to the tibial tubercle.

A static trial was collected, during which subjects were instructed to stand still with their shoulders abducted to 90°. Subjects then performed the jump-landing task first on the left side. Subjects began the task standing on one leg (test leg) on a 25.4-cm step with their hands on their hips and the contralateral leg slightly flexed at the knee. Subjects then hopped off the step and landed on the test leg on a force plate. Subjects were cued to keep their eyes forward and to keep the contralateral knee bent and behind the test leg. Subjects observed a visual demonstration and performed at least two practice trials before the test trials. A test trial was considered successful if the subject made solid foot contact with force plate and maintained balance on the test leg for 3 s. Testing was repeated until a successful trail was obtained, and then repeated using the right side as the test leg.

Data analysis. Three-dimensional marker trajectories examined using the motion capture system were then exported to a coordinate 3D file format. Commercial software (Visual3D; C-Motion Inc., Germantown, MD) was used to process kinetic and kinematic data. The ground reaction force was filtered through a low-pass Butterworth filter at a cutoff frequency of 15 Hz. Marker data were low-pass filtered using a fourth-order Butterworth filter at 6 Hz to create a six-degree-of-freedom rigid body model. The markers on the iliac crests and greater trochanters were used to construct a cylindrical model for the pelvis segment. For the thigh segment, a truncated cone model was created proximally with the greater trochanter marker and the bisection of the greater trochanter markers and distally with the femoral condyle markers. The greater trochanter

TABLE 1. Demographic data for subjects with concussion and uninjured subjects.

	With Concussion (n = 13)	Uninjured (n = 26)	P
Age (yr)	19.5 ± 0.7	19.7 ± 1.1	0.369
Height (cm)	187.0 ± 7	187.1 ± 6	0.958
Weight (kg)	101.5 ± 16.6	100.5 ± 17.5	0.843
Time from concussion to postseason testing (d)	49.9 ± 24.2	N/A*	N/A
Time missed from concussion (d)	8.8 ± 7.6	N/A	N/A

marker, the lateral femoral condyle marker, and the thigh marker tracked the thigh segment. The femoral condyle and malleoli markers created a truncated cone model for the shank. The lateral femoral condyle marker, the shank marker, and the lateral malleoli marker tracked the shank segment.

The hip joint centers were positioned in line with their respective greater trochanter marker at one-fourth the total distance between greater trochanter markers. Knee joint centers were located halfway between the femoral condyle markers, and ankle joint centers were located midway between the malleoli markers. The orientation of the coordinate system placed the x-axis in the medial–lateral direction, the y-axis in the anterior-posterior direction, and the z-axis in the vertical direction.

Force and kinematic data were combined to calculate joint moments through inverse dynamics. Moments represented the external load on the joint. Kinetic and kinematic data at initial contact (when vertical ground reaction force first exceeded 20 N) and peak flexion angles as well as peak external flexion moments (kg) were calculated for the hip, knee, and ankle. Joint stiffness was modeled as a rotational spring at each joint (34). Hip, knee, and ankle angles and moments in the sagittal plane were used to calculate stiffness. A custom LabVIEW (National Instruments, Austin, TX) program calculated stiffness at each joint as the slope of the moment–angle curve from a least squares regression from initial contact to peak joint flexion (14,28). Leg stiffness was calculated as the quotient of the PVGRF and the vertical change in leg length (m) (32). Vertical change in leg length was calculated as the vertical displacement of the greater trochanter marker relative to the lateral malleolus marker. The interval of interest was from initial contact to PVGRF.

Joint and leg stiffness values were normalized to body weight to allow for comparison across subjects. The values from the two matched UNINJ subjects were averaged for all measurements to create paired data for each CONC subject.

Statistical analysis. Statistical analyses were conducted using the Statistical Package for the Social Sciences for Windows (version 22.0; SPSS Inc., Chicago, IL). Mean and standard deviation values were calculated for each variable investigated in study subjects. The variables for age, height, body weight, hip stiffness, knee stiffness, ankle stiffness, and leg stiffness were normally distributed. Thus, parametric methods were used for data analysis. For all subjects, an index was created to measure asymmetries between right and left sides ([right side − left side] × 100) for hip, knee, ankle, and leg stiffness. Paired t-tests revealed no significant differences in asymmetry indices between CONC and UNINJ groups ($P > 0.05$). Therefore, right side and left side values were averaged together for each subject. Separate Student t-tests were used to determine differences in hip, knee, ankle, and leg stiffness for CONC and UNINJ groups at both pre- and postseason test sessions. Finally, to measure the effect of group on pre- to postseason changes in hip, knee, ankle, and leg stiffness, separate univariate general linear models were created with the postseason value as the dependent variable and the preseason value, group (CONC, UNINJ), age, height, and body weight as the predictor variables. To correct for type I error related to multiple analyses, P values were adjusted using the false discovery rate. Values of $P < 0.05$ were considered significant.

RESULTS

Participants consisted of 39 Division I football players (mean ± SD, age 19.6 ± 1.0 yr, height 187.4 ± 6.4 cm, weight 100.8 ± 17.0 kg). Means for age, height, and body weight were not different ($P \geq 0.54$) between CONC subjects and UNINJ subjects (Table 1). Positions played in CONC and UNINJ subjects are presented in Table 2.

Values for kinetic and kinematic variables for the hip, knee, and ankle joints for CONC and UNINJ subjects are presented in Table 3. Preseason values for hip, knee, ankle, and leg stiffness were not statistically different between groups ($P \geq 0.90$). Similarly, postseason values for hip, ankle, and knee stiffness were not statistically different between groups ($P \geq 0.08$). Values for hip, knee, and leg stiffness are presented in Figure 1. The general linear model revealed significant effects of group (CONC vs UNINJ) for hip ($F = 6.37$, $P = 0.03$), knee ($F = 5.48$, $P = 0.03$), and leg stiffness ($F = 9.46$, $P = 0.03$) for the change values from pre- to postseason. However, there was no effect of group for ankle stiffness ($F = 2.06$, $P = 0.653$) for the change value from pre- to postseason. In addition, there was no effect of age ($P \geq 0.07$), height ($P \geq 0.24$), or weight ($P \geq 0.48$) for hip, knee, ankle, and leg stiffness on the change from pre- to postseason values.

DISCUSSION

The purpose of this study was to compare pre- to postseason changes in stiffness across the lower extremity during jump landing in athletes with and without a recent concussion. As hypothesized, the CONC group demonstrated altered stiffness from pre- to postseason when compared

TABLE 2. Position played for subjects with concussion and uninjured subjects.

	With Concussion (n = 13)	Uninjured (n = 26)
Wide receiver	3	6
Running back	1	2
Tight end	1	2
Offensive line	1	2
Defensive line	3	6
Line backer	3	6
Cornerback	1	2

TABLE 3. Hip, knee, and ankle kinetic and kinematic data for subjects with concussion and uninjured subjects.

	With Concussion (n = 13)		Uninjured (n = 26)	
Joint	Preseason	Postseason	Preseason	Postseason
Hip				
Angle at initial contact (°)	19.9 ± 7.3	22.1 ± 5.9	19.6 ± 6.5	21.35 ± 7.3
Peak flexion angle (°)	39.9 ± 9.0	46.0 ± 8.9	38.5 ± 10.0	42.66 ± 9.3
Peak moment (N·m per body weight)	2.9 ± 0.8	2.5 ± 0.5	2.9 ± 1.0	2.8 ± 0.7
Knee				
Angle at initial contact (°)	10.5 ± 3.6	11.0 ± 3.8	7.9 ± 5.1	11.2 ± 3.6
Peak flexion angle (°)	51.1 ± 6.2	55.5 ± 6.8	48.9 ± 7.8	50.6 ± 6.6
Peak moment (N·m per body weight)	2.2 ± 0.4	2.3 ± 0.4	2.6 ± 0.4	2.7 ± 0.5
Ankle				
Angle at initial contact (°)	−21.2 ± 5.3	−22.9 ± 5.1	−20.0 ± 8.0	−19.6 ± 4.2
Peak flexion angle (°)	21.0 ± 4.00	23.5 ± 4.0	22.8 ± 2.9	21.5 ± 2.6
Peak moment (N·m per body weight)	2.3 ± 0.4	2.2 ± 0.30	2.3 ± 0.3	2.3 ± 0.3

with the UNINJ group. Specifically, knee and leg stiffness decreased, whereas hip stiffness increased in the CONC group. Because stiffness of the lower extremity is controlled by the neuromuscular system, these findings provide further evidence of changes in neuromuscular function after return to play from concussion.

Pre- to postseason changes in lower extremity stiffness were compared between CONC and UNINJ groups so that the effects of concussion could be isolated from changes that might normally occur during the season. At preseason testing, there were no differences in stiffness measures between the CONC and the UNINJ groups. In addition, preseason leg stiffness values in CONC and UNINJ approximate the leg stiffness value of 19.4 body weight per meter reported in healthy physically active males during unilateral hopping (3). This suggests that stiffness of the lower extremity was not altered in the CONC at the start of the season. Leg stiffness decreased in the CONC group, but joint stiffness showed differential change, with an increase at the hip and decrease at the knee. When compared with preseason values, CONC subjects demonstrated altered component of knee stiffness, including increased peak knee moment and decreased knee angular excursion. Altered landing mechanics at the knee may be related to changes in quadriceps function. Specifically, pilot data from our laboratory indicated decreased quadriceps strength in collegiate football players after concussion (14). Landing with decreased knee angular excursion after concussion may reflect an attempt to increase knee stability because with less knee flexion, subjects rely more on ligamentous tissue, the tightened collateral ligaments, to stabilize the knee (1). Similarly, Martini et al. (23) reported that when compared with nonconcussed controls, athletes with a concussion attempt to increase stability during gait by adopting a conservative gait strategy (slower

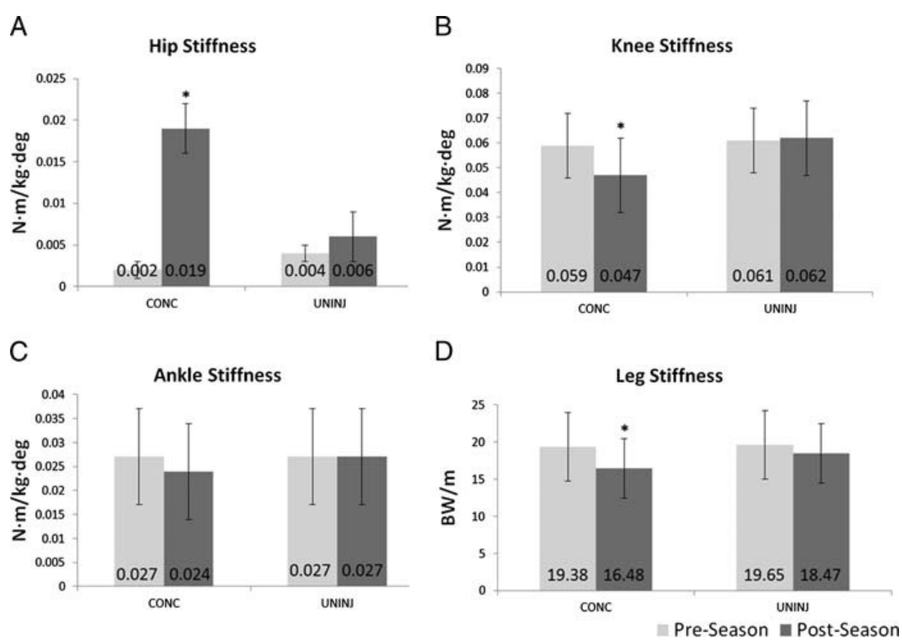

FIGURE 1—Stiffness parameters. Mean values for hip stiffness (A), knee stiffness (B), ankle stiffness (C), and leg stiffness (D) for subjects with concussion (CONC) and uninjured controls (UNINJ) at pre- and postseason. At each joint, the internal joint extensor moment, normalized to body weight, was plotted against joint flexion angle from initial contact to peak flexion. The slopes of regression lines represented stiffness at each joint. Leg stiffness equaled the PVGRF/vertical displacement of the lower extremity from initial contact to PVGRF. *Statistically significant effect of group (CONC vs UNINJ) for the change values from pre- to postseason ($P \leq 0.05$).

velocity, greater time in double leg stance, and less time in a single-leg stance). In addition, compared with preseason testing, CONC subjects in our study demonstrated decreased hip peak moment and increased hip angular excursion at postseason testing. When the trunk is positioned over the knee with increased hip flexion, it has been reported that hamstring activation may increase whereas quadriceps activation decreases (37). Our findings of altered leg, hip, and knee stiffness during a jump-landing task after concussion add to findings of altered movement patterns in other tasks such as gait and running.

Altered movement patterns after concussion may be due to a diminished capacity for motor planning (23). Neuroimaging studies have documented impaired motor planning due to alterations in the motor cortex after concussion, including increased intracortical inhibition, reduced intracortical excitability, and decreased metabolic activity that persists despite the resolution of symptoms (9,10,29,31,35). Collectively, alterations in the motor cortex could affect all aspects of motor control, including motor planning, muscle recruitment, and coordination. For example, researchers have documented changes in motor recruitment and muscle strength in athletes postconcussion (13,33). After concussion, ice hockey players demonstrated decreased leg maximal voluntary contraction (33). Also, as previously mentioned, decreased quadriceps strength has been demonstrated in collegiate football players after concussion (14). Quadriceps voluntary activation failure may affect knee movement patterns and has not been thoroughly studied after concussion. However, voluntary activation failure has been demonstrated in the hand musculature after concussion (29,31). If similar voluntary activation findings exist in the quadriceps musculature, reduced voluntary activation may cause deficits in quadriceps strength, slower movement time, and reduce peak force, subsequently affecting stiffness across the lower extremity (8,26).

Altered stiffness across the lower extremity after concussion may increase the risk of subsequent lower extremity injury. Several authors have reported greater rates of lower extremity injury in athletes with a recent concussion compared with nonconcussed controls, with the greatest number of injuries at the knee/thigh region, ankle, and the hip/groin region, respectively (4,21,27,30). During a unilateral hopping task, individuals without concussion and with Achilles tendinopathies demonstrated decreased leg stiffness when compared with uninjured controls (22). Similarly, our findings of decreased leg stiffness in athletes after concussion may be linked to a commonly injured region after concussion, the ankle. Conversely, increased leg stiffness was found prospectively in athletes who went on to sustain a hamstring injury when compared with uninjured controls (36). Although Watsford et al. (36) demonstrated increased leg stiffness in athletes who went on to obtain a hamstring injury, it is important to note that in the injured group higher stiffness was reported in the noninvolved limb. Accordingly, when comparing between limbs, decreased leg stiffness was related to greater risk of hamstring injury. Future studies should examine the underlying mechanisms for increased musculoskeletal injury after concussion; however, our findings provide additional support for altered neuromuscular control after concussion.

A strength of this study is the inclusion of the UNINJ group matched by age, season, and position. The UNINJ group provides evidence that the documented changes in neuromuscular function in the CONC group may be attributed to concussion because both groups were exposed to similar practices, strength and conditioning programs, and game opponents. The time range from return to play to postseason testing (approximately 50 d) is also important to consider. This time range is somewhat wide seeing as the average time from concussion to return to play is approximately 7–10 d (24). Stiffness alterations immediately after concussion are unknown and may have resolved from the time of return to play to concussion. However, the presence of this relationship between concussion and stiffness across the lower extremity, even with the wide time range, is consistent with others findings of increased risk of lower extremity up to 1-yr postconcussion (21). Another limitation is that the subjects were all male collegiate football players, which limits the ability to generalize to other athletes with concussion. However, the incidence of concussion in football players is high. Future studies should examine neuromuscular changes in a larger, more diverse athletic population. Another limitation is that only one test trial per leg was collected because of time constraints imposed by administering a comprehensive musculoskeletal screening to a large number of athletes. Therefore, we caution against using the values in this study as normative data. We partially compensated for this limitation by averaging trials from the right and left sides for each subject. It is also important to note that this study is retrospective and, therefore, depended on record keeping to identify both CONC and UNINJ subjects.

In conclusion, after concussion, collegiate football players exhibited greater alterations in stiffness across the lower extremity when compared with uninjured controls. The return to play decision is multifaceted and complex; however, current concussion management protocols do not incorporate neuromuscular measures from a high-demand athletic task. Considering the increased risk of lower extremity injury after concussion, return to play guidelines may be improved by the inclusion neuromuscular evaluations. Although more research is needed, our findings of subclinical altered stiffness across the lower extremity imply that neuromuscular function may be altered after concussion.

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