Annals of Biomedical Engineering (© 2013)
DOI: 10.1007/s10439-013-0881-8

The Effect of Visual and Sensory Performance on Head Impact Biomechanics in College Football Players

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(Received 30 April 2013; accepted 24 July 2013)

Associate Editor Stefan M. Duma oversaw the review of this article.

Abstract—The development of prevention strategies is critical to address the rising prevalence of sport-related concussions. Visual and sensory performance may influence an individual's ability to interpret environmental cues, anticipate opponents' actions, and create appropriate motor responses limiting the severity of an impending head impact. The purpose of this study was to determine the relationship between traditional and visual sensory reaction time measures, and the association between visual and sensory performance and head impact severity in college football players. Thirty-eight collegiate football players participated in the study. We used real-time data collection instrumentation to record head impact biomechanics during games and practices. Our findings reveal no significant correlations between reaction time on traditional and visual sensory measures. We found a significant association between head impact severity and level of visual and sensory performance for multiple assessments, with low visual and sensory performers sustaining a higher number of severe head impacts. Our findings reveal a link between level of visual and sensory performance and head impact biomechanics. Future research will allow clinicians to have the most appropriate testing batteries to identify at-risk athletes and create interventions to decrease their risk of injurious head impacts.

Keywords—Concussion, Football, Injury prevention, Kinematics, Mild traumatic brain injury, Sports biomechanics, Vision.

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INTRODUCTION

Concussion has been defined as a complex pathophysiologic process affecting the brain, induced by traumatic biomechanical forces that typically result in an impairment of neurologic function and clinical symptoms such as disturbances of vision and equilibrium.[18] Sport-related concussions have become a major public health concern, with approximately 3.8 million sports-related traumatic brain injuries occurring in the United States each year.[16] The majority of sport-related concussions occur in contact or collision sports such as football, which is one of the most popular sports among high school and collegiate males.[1,4] Sport-related concussions respectively accounted for 5.8 and 8.9% of all collegiate and high school football injuries.[6,11]

Mechanisms of injury for concussions include both direct and indirect head impacts,[13] resulting in a combination of two types of forces: linear and rotational.[2] Evidence linking the magnitude, direction, and distribution of the forces applied to the brain and resulting injury has been previously established in animal and modeling studies[14,22]; recent studies suggest these links may exist with respect to human head trauma.[13,24,31] Decreasing linear and angular acceleration forces associated with high magnitude impacts decreases a person's risk of sustaining a concussion. While this may be accomplished to some extent by using helmets,[23,29] helmets alone cannot prevent concussion,[13] and are not used in all sports. Thus, researchers have studied collision anticipation in an attempt to understand the causes and factors related to concussion. Anticipated collisions are associated with

Published online: 06 August 2013

less severe head impacts in youth ice hockey players[20]; however, this has not been extensively studied in collegiate football players. Visual and sensory performance, referring to the manner the brain receives sensory information from the eyes, integrates that with somatosensory and vestibular input from other sensory inputs, and produces an appropriate motor response, may influence anticipation and affect an individual's ability to withstand head impact forces. Individuals with higher levels of visual and sensory performance, including the characteristics of visual acuity and contrast sensitivity, are able to respond to their environment in a more efficient and appropriate way.[32] Visual training has been found to be transferable to the performance of athletes.[27] Several tools exist to evaluate and train components of an individual's level of visual and sensory performance. An athlete's visual and sensory performance may not only be relevant to performance but also to their ability to anticipate and react to impending head impacts on the field, ushering in a new area of research with the goal of preventing injury while concurrently improving athlete performance.

Evaluation of visual and sensory performance may be implemented to identify at-risk athletes, and lead to prospective interventions designed to decrease an athlete's overall risk of sustaining injurious head impacts. In addition, an evaluation of visual and sensory performance includes an assessment of an athlete's functional reaction time, in place of traditional computerized neurocognitive tests that are far dissimilar to the reaction time demands that are ultimately experienced by athletes in their sports. Identifying the relationships between traditional measures of reaction time and visual sensory reaction time as measured by the Nike SPARQ Sensory Station will provide insight regarding the development of more appropriate testing batteries to evaluate an athlete's level of visual and sensory performance to be used for injury prevention interventions. Therefore, the purposes of this study were to (1) explore the relationship between traditional measures of reaction time and reaction time as measured by the Nike SPARQ Sensory Station and (2) to evaluate whether visual and sensory performance had an effect on head impact biomechanics as measured by linear acceleration, rotational acceleration, and Head Impact Technology severity profile (HITsp) in college football players. For the latter, we hypothesized college football players with relatively high performance on visual and sensory performance measures would experience lower linear acceleration, rotational acceleration, and HITsp.

MATERIALS AND METHODS

Study Design and Participants

We employed a prospective quantitative research design in order to address our study objectives. We recruited 38 Division I college football players from the University of North Carolina at Chapel Hill Fall 2012 football team (age = 20.4 ± 1.4 years; height = 190.2 ± 6.7 cm; mass = 109.3 ± 17.8 kg). Participants were selected based on input from the coaching and sports medicine staff to include a variety of player positions including 2 quarterbacks, 3 wide receivers, 3 offensive backs, 12 offensive linemen (including tight ends), 12 defensive backs (including linebackers), and 6 defensive linemen who would be actively participating in practices and games. All participants signed an informed consent form approved by the university institutional review board prior to participation in the study. Inclusion criteria required that participants must be a Division I collegiate football player during the Fall 2012 season, who wore a helmet equipped with the Head Impact Telemetry System, and consented to participating in the study. Exclusion criteria included anyone who had a history of permanent vision loss or was currently symptomatic from a head, neck, or eye injury that would have negatively affected scores on visual and sensory performance tasks.

Instrumentation

Head Impact Telemetry (HIT) System

The HIT System (Simbex, Lebanon, NH) was used to collect helmet linear acceleration, rotational acceleration, and Head Impact Technology severity profile (HITsp) data. The HIT System is comprised of six spring-loaded single-axis accelerometers inserted into Riddell VSR4 (sizes: L or XL), Revolution (sizes: M, L, or XL), or Revolution Speed (sizes: M, L, or XL) football helmets (Riddell Corporation) and the Sideline Response System. The in-helmet accelerometers are strategically placed to allow for measurement of linear and rotational acceleration and impact location. Up to 100 separate head impacts can be stored in the on-board memory built into the accelerometer. The accelerometers collect data at 1 kHz for a period of 40 ms; 8 ms are recorded before the data collection trigger and 32 ms of data are collected after the trigger. The HIT System can collect data from up to 64 players over a distance greater than the length of a football field. The Sideline Response System was located on the sideline during games and practices. This unit receives time-stamped, encoded data from the in-helmet accelerometers through a radiofrequency telemetry link. The data are processed through a novel algorithm to determine location and magnitude of impacts.[5] The user can access these data through the Head Impact Telemetry Impact Analyzer software on laptop in the Sideline Response System unit. The HIT System measures linear acceleration (measured in terms of gravitational acceleration, g), rotational acceleration (measured in rad/s^2), and Head Impact Technology severity profile (HITsp). The HITsp is a weighted composite score encompassing linear and rotational accelerations, Gadd Severity Index, Head Injury Criterion, and impact location. The HIT System is a valid measure of head impact biomechanics.[3,7]

Nike SPARQ Sensory Station

The Nike SPARQ Sensory Station is an evaluation and training tool of visual and sensory performance designed for athletes. The Nike SPARQ Sensory Station is an interactive touch screen device consisting of a single computer that controls two high-resolution LCD monitors (a 22 inch and a 42 inch monitor). An Apple iPod Touch is also used for some of the assessments.[10] See Table 1 for a description and testing procedures for each evaluation component. The Nike SPARQ Sensory Station has been found to be a reliable measure of visual and sensory performance with no significant changes in performance between multiple sessions on Visual Clarity, Contrast Sensitivity, Depth Perception, Target Capture, Perception Span, and Reaction Time. However, an expected learning effect was found for performance on Near–Far Quickness, Eye-Hand Coordination and Go/No Go across two testing sessions separated by a period of about 1 week.[10]

Reaction Time Assessments

In addition to the reaction time outcome measures include with the SPARQ Sensory Station testing, the participants underwent a series of reaction time assessments including: (1) the Stroop test, (2) Simple Reaction Time, (3) Procedural Reaction Time, and (4) Clinical Reaction Time Apparatus. Participants completed a computerized version of the Stroop test (CNS Vital Signs, LLC; Chapel Hill, NC), which measures the ability to react to a simple, but increasingly difficult set of directions in a valid and reliable manner.[12] Our outcome measure of interest was the reaction time domain score, and was calculated using the following equation:

$$[\text{Stroop Test Complex Reaction Time Correct} + \text{Stroop Reaction Time Correct}]/2$$

During the Simple Reaction Time task, the participant is instructed to left-click the mouse button in immediate response to a simple stimulus (i.e. an asterisk) appearing on the screen. We also employed a Procedural Reaction Time task, which combines a participant's reaction time and processing speed. The participant is instructed to respond as quickly as possible by left-clicking the mouse button when a '2' or '3' appear on the screen, and right-clicking the mouse button when a '4' or '5' appear on the screen. We employed the Automated Neuropsychological Assessment Metrics (Vista LifeSciences, Washington D.C.), a computerized neurocognitive test battery developed by the United States Military's Office of Military Performance Assessment Technology,[15] to validly and reliably measure Simple Reaction Time and Procedural Reaction Time.[15,26] The outcome measures combined response speed and response accuracy into a single throughput score for each task.

Lastly, the Clinical Reaction Time Apparatus is a valid and reliable clinical measure of reaction time designed for sideline or athletic training room use.[9] This simple and inexpensive device is a thin, rigid cylinder with a weighted disk attached to the bottom. The examiner holds and releases the apparatus while the individual reacts and catches it as quickly as possible using a pinch grip. Subjects completed two practice trials followed by eight trials in which the examiner released the apparatus at pre-determined randomized time intervals ranging from two to five seconds. The examiner notes the measured distance at which the most superior portion of the subject's pinch grip makes contact with the apparatus. A trial in which the subject drops the apparatus is noted as a "drop" and is not included as part of the calculation of clinical reaction time. The Clinical Reaction Time Apparatus scores are used to compute reaction time in milliseconds.

Procedures

Subjects underwent a single testing session prior to the start of the fall football season. A trained clinician administered the testing session in a quiet controlled environment in our clinical research center. All subjects completed the tests in a counterbalanced order and received standardized directions given by the administering clinician. The testing session took approximately 30–45 min. Subjects were not given any

TABLE 1. Nike SPARQ sensory station evaluation.

Test	Description	Participant set-up	Procedures
Visual break	A test of visual endurance.	Examiner holds a 24-cm ruler up with the base in between the subject's eyes. The ruler has a sliding component with a single black line in the subject's field of vision	Prior to beginning the Nike SPARQ Sensory Station Evaluation, the subject will complete the visual break test. The sliding piece is started at the maximal distance from the subject's eyes, and slowly moved closer. The subject is instructed to focus on the line for as long as possible, until it begins to blur or split to two black lines
Visual clarity	How clearly athletes see distant details.	Participant stands 16 ft from a 22-in display holding iPod Touch	Black Landolt rings (C-shaped ring) with gaps at the top, bottom, left, and right will appear in random order on a white background. Participants are instructed to swipe the iPod touch screen in the direction of the gap of the Landolt ring. The rings are preset at varying acuity demands. The procedures include binocular and monocular assessments. The examiner will isolate each eye with a vision occluder
Contrast sensitivity	Ability to pinpoint subtle differences in contrast.	Participant stands 16 ft from a 22-in display holding iPod Touch	Four black circles are presented on a light background. At random, one of the circles will contain a pattern of rings. Participants were instructed to swipe the iPod touch screen in the direction of the circle with the ring pattern
Depth perception	Speed and accuracy in judging 2-eyed depth information through multiple gaze positions	Participant stands 16 ft from a 22-in display holding iPod Touch wearing liquid crystal goggles (NVIDIA 3D Vision, Santa Clara, CA)	The goggles create a simulated depth in one of the four rings that will appear on the screen. The participant is instructed to swipe the iPod touch screen in the direction of the ring that appears closer
Near-far quickness	Quickly and accurately change visual attention between near and far distances.	Participant stands 16 ft from a 22-in display holding the iPod touch's top edge with the far display's bottom	A black Landolt ring will be presented alternating between the iPod touch screen and the screen on Nike SPARQ Sensory Station display. The participant is instructed to swipe the iPod touch screen in the direction of the gap of the Landolt ring
Target capture	Ability for rapid visual shifting and recognition of peripheral targets.	Participant stands 16 feet away from 42-inch display holding iPod Touch	The participant will focus on a central white dot until a Landolt ring appears briefly in one of the corners on the Nike SPARQ Sensory Station display. The participant is instructed to swipe in the direction of the gap of the Landolt ring that appears
Perception span	Visual quickness in acquiring critical information	Participant stands within arm's length of 42-inch display with center of screen adjusted to their height	The participant will focus on a dot in the center of a grid pattern composed of up to 30 circles. A pattern of dots will flash within the grid. The participant will use the touch screen to recreate the pattern of dots
Eye-hand coordination	Ability to make quick and accurate visually-guided hand responses to rapidly changing targets	Participant holds arms parallel to ground at shoulder height within arm's length of 42-inch display that is adjusted to their height	A grid will be presented with eight columns and six rows of equally sized and spaced circles. A dot will appear within one circle of the grid. Participant will be instructed to touch the dot as quickly as possible with either hand. As soon as they touch the dot, another dot will be presented. 96 dots will appear in a pseudorandomized sequence

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TABLE 1. continued.

Test	Description	Participant set-up	Procedures
Decision making (go/no go)	Quick and accurate decision responses to rapidly changing targets	Participant holds arms parallel to ground at shoulder height within arm's length of 42-in display	An identical grid as Eye-Hand Coordination test appears. A green or red dot will appear. If the dot is green, the participant is instructed to touch it. If the dot is red, the participant is instructed not to touch it. 96 dots will appear in a pseudorandomized sequence
Reaction time	Speed and quickness of an athlete's hand reaction in response to a visual stimulus.	Participant stands within arm's length of 42-inch display with center of screen adjusted to their height	Two annular patterns appear on the screen. Participant places dominant hand's fingertips on inner circle of pattern. This changes circle to green. Participant focuses on the center of the annular pattern in front of them. After a random delay of 2, 3, or 4 s, the second pattern turns green and athlete moves their hand to touch its inner circle as quickly as possible

feedback regarding performance during the testing session. The testing session included the Nike SPARQ Sensory Station; the Stroop, Simple Reaction Time, Procedural Reaction Time tests; and the Clinical Reaction Time Apparatus.

The team's professional equipment manager fitted all participants with football helmets capable of accepting HIT System accelerometer units at the start of the season. Head impact data were collected during practices and games throughout the course of the season. The HIT System and Sideline Response System were checked on a weekly basis and prior to all games and practices, to ensure proper functioning. Helmet fit was also verified on a regular basis by the team's equipment staff.

Data Reduction

Raw head impact data were exported from Sideline Response System using the Ridell Export Utility into Matlab 7 (The Mathworks, Inc., Natick, MA). Linear acceleration (g), rotational acceleration (rad/s^2), and HITsp were the outcome measures of interest. All impacts under 10 g were removed because impacts below this threshold make it difficult to distinguish between head impacts and voluntary head movements.[19] In order to allow for comparisons with previous research in this area, we categorized the head impact severity for linear acceleration as mild ($<$66 g), moderate (66–106 g) or severe ($>$106 g) and for rotational acceleration as mild ($<$4600 rad/s^2), moderate (4600–7900 rad/s^2), or severe ($>$7900 rad/s^2).[21,31]

We used the raw data we collected on the Nike SPARQ Sensory Station to categorize participants into one of two groups based on performance (High: ≥51st percentile; Low: ≤49th percentile) captured for each of the following measures: Visual Break, Depth Perception, Near–Far Quickness, Target Capture, Perception Span, Eye Hand Coordination, Go/No Go, and Reaction Time. These percentiles were based on our study's sample.

Statistical Analyses

Pearson product-moment correlation coefficients were calculated between traditional measures of reaction time (Stroop, Simple Reaction Time, Procedural Reaction Time, Clinical Reaction Time Apparatus) and reaction time as measured by the Nike SPARQ Sensory Station. Additionally, separate random intercepts general mixed linear models were employed for each of the dependent variables (i.e. linear acceleration, rotational acceleration, and HITsp). The distribution of head impacts is skewed by large numbers of low-magnitude impacts. Therefore, we used the natural

TABLE 2. Mean resultant linear acceleration, rotational acceleration, and HITsp of head impacts sustained by high and low performers of visual and sensory performance assessments.

	Linear acceleration (g)				Rotational acceleration (rad/s^2)				HITsp			
		95% CI				95% CI				95% CI		
	Mean	L	U	P^a	Mean	L	U	P^a	Mean	L	U	P^a
Visual break												
High performer[b]	22.4	21.3	23.5	(Ref)	1252.2	1178.7	1330.2	(Ref)	13.3	12.7	13.8	(Ref)
Low performer	22.0	21.3	22.7	0.538	1254.7	1170.0	1345.5	0.965	13.3	12.8	13.7	0.985
Depth perception												
High performer[b]	21.6	20.8	22.5	(Ref)	1215.7	1127.5	1310.7	(Ref)	13.0	12.5	13.5	(Ref)
Low performer	22.8	21.9	23.7	0.065	1290.8	1227.2	1357.8	0.188	13.5	13.0	14.0	0.161
Near–far quickness												
High performer[b]	21.9	21.0	22.9	(Ref)	1250.3	1150.1	1359.3	(Ref)	13.1	12.6	13.8	(Ref)
Low performer	22.5	21.6	23.3	0.401	1256.3	1201.4	1313.6	0.920	13.4	13.0	13.8	0.533
Target capture												
High performer[b]	21.3	20.5	22.2	(Ref)	1202.6	1121.7	1289.3	(Ref)	13.0	12.6	13.6	(Ref)
Low performer	23.1	22.4	23.8	0.004*	1305.9	1236.2	1379.5	0.068	13.5	13.0	14.0	0.213
Perception span												
High performer[b]	21.5	20.7	22.4	(Ref)	1233.4	1152.7	1319.9	(Ref)	13.0	12.5	13.5	(Ref)
Low performer	22.8	21.9	23.7	0.047*	1270.1	1192.8	1352.5	0.524	13.5	13.0	14.0	0.206
Eye-hand coordination												
High performer[b]	21.9	21.1	22.7	(Ref)	1212.2	1146.0	1282.2	(Ref)	13.1	12.7	13.6	(Ref)
Low performer	22.5	21.5	23.6	0.307	1300.4	1211.8	1395.5	0.123	13.4	12.9	13.9	0.488
Go/no go												
High performer[b]	21.6	20.8	22.5	(Ref)	1201.4	1122.4	1285.9	(Ref)	12.9	12.4	13.4	(Ref)
Low performer	22.9	22.1	23.8	0.038*	1320.9	1257.9	1387.1	0.028*	13.8	13.3	14.2	0.008*
Reaction time (SPARQ)												
High performer[b]	22.6	21.9	23.3	(Ref)	1287.9	1218.6	1361.0	(Ref)	13.5	13.0	13.9	(Ref)
Low performer	21.7	20.7	22.8	0.175	1217.9	1132.1	1310.2	0.224	13.0	12.5	13.6	0.231
Reaction time (clinical)												
High performer[b]	22.6	21.7	23.5	(Ref)	1247.7	1169.8	1330.7	(Ref)	13.3	12.8	13.9	(Ref)
Low performer	21.8	20.9	22.7	0.223	1259.0	1178.3	1345.1	0.845	13.2	12.8	13.7	0.793

[a] *P* values are relative to the reference category used by the random intercepts general mixed linear model analyses.
[b] Denotes the reference (Ref) category.

logarithmic transformations of the linear acceleration, rotational acceleration, and HITsp, so that they would be normally distributed for the purpose of linear regression statistical analyses. *Player* represented one level in each statistical model as a repeated factor. Performance level (high vs. low) served as the independent variable included in separate statistical models used to address whether differences in head impact biomechanics existed between high and low visual and sensory performers. These statistical analyses—random intercepts general mixed linear models—are more robust than traditional generalized linear models (e.g. ANOVAs) because they (1) do not assume independent samples; (2) include incomplete cases in the analysis; (3) allow subjects to be measured at different points in time (e.g. repeated head impacts); and (4) are efficient for both balanced and unbalanced designs. Lastly, Chi square analyses were performed to assess the association between visual and sensory performance (i.e. high, low) and a categorized variable of impact severity (i.e. mild, moderate, or severe) based on both linear and rotational acceleration measures. SAS Version 9.3 was used for all data analyses with an *a priori* alpha level of 0.05.

RESULTS

One participant sustained a season-ending injury during the first week of practices, and another participant replaced his helmet with one incapable of supporting the HIT System technology. For these reasons, we did not have sufficient head impact biomechanical data for these two athletes to address the effect of visual and sensory performance on head impact biomechanics. Thus, the relationships between our clinical measures of reaction time ($N = 38$), and our study of head impact biomechanics ($N = 36$) had different sample sizes.

TABLE 3. Frequency (percentage) of recorded impacts sustained by high and low performers of visual and sensory assessments by an ordinal level of head impact severity based on linear and rotational accelerations.

	Head impact severity-linear acceleration frequency (%)			Head impact severity-rotational acceleration frequency (%)		
	Mild <66 g	Moderate 66–106 g	Severe >106 g	Mild <4600 g	Moderate 4600–7900 g	Severe >7900 g
Visual break	$\chi^2 = 2.919$, $p = 0.234$			$\chi^2 = 2.91$, $p = 0.234$		
High performer	9275 (47.66)	314 (1.61)	58 (0.30)	9413 (48.37)	199 (1.02)	35 (0.18)
Low performer	9473 (48.68)	295 (1.52)	45 (0.23)	9546 (49.05)	236 (1.21)	31 (0.16)
Depth perception	$\chi^2 = 11.85$, $p = 0.003$*			$\chi^2 = 5.32$, $p = 0.070$		
High performer	8983 (46.16)	249 (1.28)	47 (0.24)	9065 (46.58)	184 (0.95)	30 (0.15)
Low performer	9765 (50.18)	360 (1.85)	56 (0.29)	9894 (50.84)	251 (1.29)	36 (0.18)
Near–far quickness	$\chi^2 = 10.04$, $p = 0.007$*			$\chi^2 = 41.75$, $p < 0.001$*		
High performer	9274 (47.66)	316 (1.62)	66 (0.34)	9337 (47.98)	281 (1.44)	38 (0.20)
Low performer	9474 (48.68)	293 (1.51)	37 (0.19)	9622 (49.45)	154 (0.79)	28 (0.14)
Target capture	$\chi^2 = 44.57$, $p < 0.001$*			$\chi^2 = 30.99$, $p < 0.001$*		
High performer	10,403 (53.46)	263 (1.35)	42 (0.22)	10,493 (53.92)	184 (0.95)	31 (0.16)
Low performer	8345 (42.88)	346 (1.78)	61 (0.31)	8466 (43.50)	251 (1.29)	35 (0.18)
Perception span	$\chi^2 = 36.32$, $p < 0.001$*			$\chi^2 = 16.24$, $p < 0.001$*		
High performer	8496 (43.66)	211 (1.08)	31 (0.16)	8557 (43.97)	159 (0.82)	22 (0.11)
Low performer	10,252 (52.68)	398 (2.05)	72 (0.37)	10,402 (53.45)	276 (1.42)	44 (0.23)
Eye-hand coordination	$\chi^2 = 2.12$, $p = 0.346$			$\chi^2 = 27.10$, $p < 0.001$*		
High performer	9814 (50.43)	305 (1.57)	49 (0.25)	9957 (51.17)	174 (0.89)	37 (0.19)
Low performer	8934 (45.91)	304 (1.56)	54 (0.28)	9002 (46.26)	261 (1.34)	29 (0.15)
Go/no go	$\chi^2 = 12.09$, $p = 0.002$*			$\chi^2 = 22.04$, $p < 0.001$*		
High performer	9875 (50.75)	289 (1.49)	42 (0.22)	9986 (51.32)	181 (0.93)	39 (0.20)
Low performer	8873 (45.60)	320 (1.64)	61 (0.31)	8973 (46.11)	254 (1.31)	27 (0.14)
Reaction time (SPARQ)	$\chi^2 = 21.17$, $p < 0.001$*			$\chi^2 = 25.19$, $p < 0.001$*		
High performer	8506 (43.71)	318 (1.63)	63 (0.32)	8603 (44.21)	246 (1.26)	38 (0.20)
Low performer	10,242 (52.63)	291 (1.50)	40 (0.21)	10,356 (53.22)	189 (0.97)	28 (0.14)
Reaction time (clinical)	$\chi^2 = 0.31$, $p = 0.856$			$\chi^2 = 19.31$, $p < 0.001$*		
High performer	7918 (40.69)	254 (1.31)	41 (0.21)	8041 (41.32)	140 (0.72)	32 (0.16)
Low performer	10,830 (55.65)	355 (1.82)	62 (0.32)	10,918 (56.10)	295 (1.52)	34 (0.17)

*Significant p values ($p > 0.05$).

Reaction Time

The Stroop test was significantly associated with Simple Reaction Time ($r = -0.328$; $p = 0.044$) and Procedural Reaction Time ($r = -0.330$; $p = 0.043$) throughput scores. Due to the nature of the data, the negative relationship indicates that as Simple and Procedural Reaction Time throughput scores increase (indicating better performance), reaction time scores obtained from the Stroop test resulted in less time necessary to complete the task (indicating better performance). We did not observe any significant correlations between computerized reaction time measures, the Clinical Reaction Time Apparatus, or the Nike SPARQ Sensory Station ($p > 0.05$ for all).

Visual and Sensory Performance

We observed significantly higher linear acceleration in low performers compared to high performers on Target Capture ($F_{1,35} = 9.56$; $p = 0.004$), Perception Span ($F_{1,35} = 4.22$; $p = 0.047$), and Go/No Go ($F_{1,35} = 4.63$; $p = 0.038$) visual and sensory performance assessments. Additionally, low Go/No Go performers experienced greater rotational acceleration ($F_{1,35} = 5.29$; $p = 0.028$) and HITsp ($F_{1,35} = 7.84$; $p = 0.008$) than high performers.

We observed a significant association between linear acceleration severity (mild, moderate, or severe) and level of visual and sensory performance on the following Nike SPARQ Sensory Station assessments: Reaction Time ($\chi^2[2] = 21.166$, $p < 0.001$), Target Capture ($\chi^2[2] = 44.572$, $p < 0.001$), Near–Far Quickness ($\chi^2[2] = 10.042$, $p = 0.007$), Depth Perception ($\chi^2[2] = 11.852$, $p = 0.003$), and Go/No Go ($\chi^2[2] = 12.092$, $p = 0.002$). We additionally observed a significant association between rotational acceleration severity (mild, moderate, or severe) and the following assessments: Nike SPARQ Sensory Station Reaction Time ($\chi^2[2] = 25.187$, $p < 0.001$), Clinical Reaction Time Apparatus ($\chi^2[2] = 19.311$, $p < 0.001$), Target Capture ($\chi^2[2] = 30.986$, $p < .001$), Near–Far Quickness ($\chi^2[2] = 41.754$, $p < 0.001$), Perception Span ($\chi^2[2] = 16.244$, $p < 0.001$), Eye-Hand Coordination ($\chi^2[2] = 27.096$, $p < 0.001$), and Go/No Go ($\chi^2[2] = 22.038$, $p < 0.001$). All descriptive and statistical information is provided in Tables 2 and 3.

DISCUSSION

The most important finding of our study was that there was a significant association between head impact severity and performance on certain visual and sensory performance assessments in college football players. Specifically, there was a strong association between level of performance on Perception Span, Target Capture, Go/No Go, and Depth Perception and head impact severity, with lower performers sustaining more severe head impacts. These are all complex tests that require a higher level of attentional focus, which may explain their association to head impact severity in college football. In the future, these tests should be incorporated into preventative visual and sensory training programs to decrease the risk of sustaining injurious head impacts.

Reaction Time

Relationships between the Stroop test reaction time, Simple Reaction Time, and Procedural Reaction Time exist. These three tests were all administered through traditional computerized neurocognitive test batteries. However, our data did not support our hypothesis that there would be a significant correlation between scores on traditional measures of reaction time and clinical or visual and sensory performance measures. Previous research has shown performance on the Clinical Reaction Time Apparatus was correlated with performance on computerized reaction time tests.[8] One reason for the difference in results could be that the previous study used a much larger sample of college football players. Given our results, it is possible that clinical and visual sensory reaction time measures may provide additional information to clinicians. The Clinical Reaction Time Apparatus requires a very different motor (pinch grasp) action in response to the reaction stimulus (i.e. dropping the apparatus). Likewise, the visual sensory reaction time requires a physical movement of the hand from one target to another target in response to a visual (light) stimuli. Although these all allow for reaction time to be measured, the underlying neuromuscular mechanisms by which reaction times are measured are different. As a result, we submit these findings suggest that computerized testing alone may lack the ability to provide a true representative measure of the functional reaction time that is necessary for athletes to participate safely during sports. Further study exploring the utility of clinical and visual sensory reaction time measures in the context of concussion management and developing injury prevention strategies is warranted.

Visual and Sensory Performance

The most important finding of our study was that there was a significant association between head impact severity and performance on certain visual and sensory performance assessments in college football players. Our data supported our hypothesis that a high level of visual and sensory performance is associated with less severe head impacts. Previous research has found that individuals with higher levels of certain aspects of visual and sensory performance, including the characteristics of visual acuity and contrast sensitivity, are able to respond to their environment in a more efficient and appropriate way.[32]

We observed a significant association between performance on Perception Span and severity of head impact, with low performers sustaining twice as many severe head impacts than high performers (see Table 3 for frequencies). We saw similar associations between performance on Target Capture, Depth Perception, and Go/No Go assessments. This cluster of Nike SPARQ Sensory Station assessments are all unique tests that challenge the subject to quickly and accurately obtain information from a combination of central and peripheral targets through multiple gaze positions. Additionally, Perception Span, Target Capture, and Go/No Go are all complex tasks that require a higher processing demand. The choice component involved with these assessments requires a higher level of attentional focus to execute at maximal speed with minimal error. The complexity of this cluster of assessments may explain for the strong association to head impact severity. In a sample of college football players, a low level of visual and sensory performance on these assessments could indicate that the athletes are not able to interpret environmental cues, anticipate actions of opponents, and create an appropriate motor response to limit the severity of an impending head impact. Unfortunately, our study did not employ video analysis to distinguish between anticipated and unanticipated collisions, nor did we analyze the distinction between active (striking player) and reactive (player struck) collisions. Future studies in this area may benefit from video analyses and classification of impacts.

Previous research in visual search behavior and fixation patterns have found that experts tend to have more pertinent search strategies and more frequent fixations of shorter duration early on in the task,[17,30] giving themselves just enough time to extract the appropriate information.[25] A fixation of longer duration on a particular target, which may be seen in a low performer on these visual and sensory performance tasks, may limit an athlete's ability to anticipate and prepare for an impending impact.[28] The findings of our study reveal a need for future research that would study the effectiveness of a visual and sensory training program in decreasing the risk of sustaining injurious head impacts. Specifically, preventative visual and sensory training programs should include the complex attentional tests: Perception Span, Target Capture, Go/No Go, and Depth Perception, which we found to be most predictive of low performers sustaining more severe head impacts. With limited study in this area available in the literature, it is impossible for us to determine our findings as causative. For example, it is possible that some players have accumulated large exposures to head impact trauma during their playing careers that have led to deficits in visual and sensory performance. Thus, our study design did not allow us to evaluate this alternative hypothesis. In light of this, we submit that future study should include a youth football sample. Youth players have not accumulated head impacts over time and, thus, we would be able to further study the interaction between head impact severity and visual and sensory performance.

Visual and Sensory Performance Following Concussion

Two subjects in our study sustained concussions during the data collection period. Injured subject 1 was a linebacker who sustained a concussion during the third quarter of a game while tackling an opponent. This subject was a low performer in six of the nine assessments included in our data analysis (Visual Break, Depth Perception, Near–Far Quickness, Perception Span, Eye Hand Coordination, and Go/No Go). Injured subject 2 was a tight end who sustained a concussion during kick off on a helmet-to-helmet collision. This subject was a low performer in three of the nine assessments (Target Capture, Perception Span, Reaction Time on Nike SPARQ Sensory Station).

Subjects 1 and 2 were both re-evaluated on the Nike SPARQ Sensory Station at 11 days post-injury and 26 days post-injury, respectively. Both subjects were no longer symptomatic and had performed comparable to baseline on computerized neurocognitive and postural testing and were cleared to return to physical activity by their team physician. Subject 1 had the following deficits between his pre and post-injury evaluations: 55% on Contrast Sensitivity, 44% on Depth Perception, 10% on Near–Far Quickness, 5% on Go/No Go, and 13% on Reaction Time. Subject 2 had the following deficits between his pre and post-injury evaluations: 32% on Contrast Sensitivity, 6% on Near–Far Quickness, and 16% on Perception Span.

It should be noted that these two athletes might have intentionally used their head to strike opponents. Employing this tackling technique may negatively affect visual and sensory performance. Thus, the deficits observed may be the result of poor tackling technique and not directly related to the actual injury. Unfortunately, our study did not employ video analysis to distinguish between anticipated and unanticipated collisions, nor did we analyze the distinction between active (striking player) and reactive (player struck) collisions. Future studies in this area may benefit from video analyses and classification of impacts. Notwithstanding, using visual and sensory performance assessment tools to determine deficits following a concussion may allow clinicians to have another tool to be incorporated into more sport-relevant return to play guidelines. While the two concussed subjects represent a very small sample size with regards to statistically significant findings, the post-injury evaluation deficits reveal a possibility for additional future research.

CONCLUSION

The findings of our study reveal a link between level of visual and sensory performance and head impact biomechanics in college football players. It is likely that an athlete's visual and sensory performance may be related to their ability to anticipate and react to impending head impacts on the field. Specifically, there was a strong association between level of performance on Perception Span, Target Capture, Go/No Go, and Depth Perception and head impact severity, with lower performers sustaining more severe head impacts. Future research should include these tests to identify at-risk athletes and create preventative training interventions to hopefully decrease their overall risk of injurious head impacts.

ACKNOWLEDGMENTS

This study was supported in part by the Centers for Disease Control and Prevention and the National Operating Committee on Standards for Athletic Equipment. None of the authors have any financial interest in any of the systems used for this study. We thank Nike for the provision of equipment used in this study.

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