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Can a Clinical Test of Reaction Time Predict a Functional Head-Protective Response?

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Abstract

Purpose—Reaction time is commonly prolonged after a sport-related concussion. Besides being a marker for injury, a rapid reaction time is necessary for protective maneuvers that can reduce the frequency and severity of additional head impacts. The purpose of this study was to determine whether a clinical test of simple visuomotor reaction time predicted the time taken to raise the hands to protect the head from a rapidly approaching ball.

Methods—Twenty-six healthy adult participants recruited from campus and community recreation and exercise facilities completed two experimental protocols during a single session: a manual visuomotor simple reaction time test (RT_{clin}) and a sport-related head-protective response (RT_{sprt}). RT_{clin} measured the time required to catch a thin vertically oriented device on its release by the tester and was calculated from the distance the device fell before being arrested. RT_{sprt} measured the time required to raise the hands from waist level to block a foam tennis ball fired toward the subject's face from an air cannon and was determined using an optoelectronic camera system. A correlation coefficient was calculated between RT_{clin} and RT_{sprt} , with linear regression used to assess for effect modification by other covariates.

Results—A strong positive correlation was found between RT_{clin} and RT_{sprt} ($r = 0.725$, $P < 0.001$) independent of age, gender, height, or weight.

Conclusions— RT_{clin} is predictive of a functional sport-related head-protective response. To our knowledge, this is the first demonstration of a clinical test predicting the ability to protect the head in a simulated sport environment. This correlation with a functional head-protective response is a relevant consideration for the potential use of RT_{clin} as part of a multifaceted concussion assessment program.

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The University of Michigan has applied for a provisional patent for the clinical reaction time device described in this article with four of the study authors listed as coinventors (J. T. E., H. K., J. K. R., and J. A. A. M.). At this time, the authors have no professional, financial, or commercial relationships with any companies or manufacturers who will benefit from the results of the present study.

The authors state that the results of the present study do not constitute endorsement by the American College of Sports Medicine.

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Keywords

CLINICAL ASSESSMENT; GENDER; INJURY AVOIDANCE; SPORT CONCUSSION

Concussion is a heterogeneous injury with variable presentation. Although every concussive injury is unique, some common signs and symptoms of concussion include headache, dizziness, visual disturbance, amnesia, fatigue, sluggishness, nausea, impaired postural stability, and cognitive or mental status changes (20,24). Another common and important sequela of concussion is prolongation of reaction time. Prolongation of both simple and choice reaction times is typical immediately after a sport-related concussion, with a gradual return to baseline over time (8,9,15,18,23,25,31,32). The presence of impaired reaction time has been shown to parallel other common postconcussive symptoms (8,9) and, in some cases, to persist even beyond full symptom resolution (32).

Current guidelines for returning an athlete to play after concussion stress the value of a multifaceted concussion assessment as well as ensuring complete recovery before return to sport (17,27,28). Although resolution of self-reported symptoms remains a key factor in the return-to-play decision-making process, the importance of persistent postural stability and neurocognitive deficits, including prolonged reaction time, in concussion management is increasingly recognized. It is generally believed that premature return to play after concussion should be avoided because an actively concussed athlete's brain has a higher physiological risk for further potentially more severe injury (11). In support, there are experimental animal data that suggest a period of increased neuronal vulnerability after concussion, with recurrent insult during this period leading to increased neuronal damage and poorer outcomes compared with a similar insult occurring in the absence of previous concussive injury (19,21,22). The most extreme example of this phenomenon is the rare but devastating second impact syndrome (2,26).

Beyond an increased physiological susceptibility of the concussed brain to additional injury, performance-related sequelae of concussion may also place an athlete at increased risk for sustaining repeated head impacts. There is growing interest in the effects of concussion on dynamic motor function. Numerous studies have demonstrated post-concussive deficits in gait stability, balance control, and obstacle avoidance in the context of susceptibility to recurrent concussive injuries (3–6,29,30). Sport participation requires intact dynamic motor control to avoid falls as well as contact with other players or objects in the athletic environment that can lead to head injury. We hypothesize that the prolongation of reaction time typically present after concussion also places an athlete at increased risk for additional head impact because of an inability to rapidly respond to the dynamic sporting environment. It follows that functional impairments due to prolonged reaction time after concussion would delay the initiation of protective maneuvers and therefore place an athlete at risk for recurrent more severe head injury.

To our knowledge, no clinical tool has been shown predict an athlete's functional ability to protect him or herself from head trauma. We have previously described the reliability and validity of a simple computer-independent method for measuring simple visuomotor reaction time that can be carried out during a sideline or training room concussion

evaluation (12). We have demonstrated in NCAA Division I athletes that this clinical measure of reaction time (RT_{clin}) correlates with simple reaction time, as measured using the CogState-Sport computerized neuropsychological test program (14) and that RT_{clin} is approximately 15% slower after a concussion compared with an athlete's own preseason baseline (13). In this study, we sought to determine whether this simple clinical test of reaction time could predict a functional sport-related head-protective response. The purpose of this study, therefore, was to test the hypothesis that RT_{clin} would be significantly correlated with the time required to manually protect the head from an oncoming ball in a simulated sport environment (RT_{sprt}).

METHODS

Subjects

A gender-balanced group of 26 healthy adults gave informed written consent to participate in this study. This research was approved by the institutional review board at the University of Michigan. In an effort to enroll athletes, recruitment efforts were focused on campus and community recreation and exercise facilities. This sample size was based on a statistical power calculation showing that 25 subjects were required to detect a correlation between RT_{clin} and RT_{sprt} of $r = 0.6$ (at α level $P = 0.05$ and 90% power). All participants were instructed to avoid alcohol for at least 48 h before their test session, to get “a good night's sleep” before the day of testing, and to consume their typical caffeine quantity on the morning of testing. Potential subjects were excluded if they were pregnant; if their corrected vision was less than 20/40; if they had a history of pulmonary, renal, hepatic, neuromuscular, or musculoskeletal disease that could impair their ability to complete the testing protocol; or if they were taking any medication with known effects on the central or peripheral nervous system with the potential to affect reaction time.

Experimental Procedures

Each study participant underwent RT_{clin} and RT_{sprt} testing during a single test session. The order of RT_{clin} and RT_{sprt} testing was randomized between subjects.

Clinical reaction time—We used a modified version of our previously described clinical reaction time apparatus to measure RT_{clin} (12) (Fig. 1). The apparatus consisted of a 117-cm-long shaft with an elliptical cross section measuring $15 \times 42 \text{ mm}^2$, in which the two long “sides” had a concavity of 5 mm running the length of the lightweight urethane foam and carbon fiber structure. At the base of the shaft, a rectangular acrylic housing measuring $3 \times 6 \times 9 \text{ cm}^3$, termed the finger “spacer,” was equipped with a half-tennis ball to absorb shock when inadvertently dropped on the ground. The entire device weighed 470 g. The spacer and shaft cross-sectional shape were designed to encourage subjects to catch the device using a pinch grip. The spacer also housed electronics enabling the apparatus to measure recognition reaction time, which was not used for this experiment. A self-adhesive metric measuring tape was affixed along one side of the shaft.

Similarly to our previous RT_{clin} test protocol (12), subjects stood with their dominant forearm resting comfortably on an adjustable horizontal table surface. Adhesive cloth tape

was wrapped around the tips of the subject's first and second digits to increase contact friction with the device shaft in the upcoming test. The examiner held the shaft vertically like a plumb bob with the 3-cm spacer separating the subject's thumb and index fingers readied in a pinch grip posture near the edge of the table. The subject was instructed to just not touch the spacer. When the subject was ready, the examiner released the device after predetermined randomly assigned time delays ranging from 2 to 5 s. The subject was instructed to catch the device as quickly as possible using a pinch grip once it began to fall. Subjects were given four practice trials to familiarize themselves with the test protocol before data were collected over eight trials. RT_{clin} was calculated based on the distance the apparatus fell before being arrested, as measured using the millimeter tape along the side of the shaft (12).

Functional sport-related head-protective reaction time— RT_{sprt} was measured by having subjects use both hands to intercept and block a bright yellow foam tennis ball (Gamma Sports, Pittsburgh, PA; 43 g, 70 mm in diameter) that was fired in the midsagittal plane directly at their face from an air cannon (Fig. 2). Subjects wore a protective ice hockey face mask and helmet as well as a chest protector for safety. The helmet had a planar cardboard surrounding attached to help the experimenter identify misfires where the ball missed the helmet by >15 cm. Subjects stood 8.25 m away from the muzzle of the cannon with their feet shoulder-width apart, knees gently flexed, and hands resting on their hips. The foam ball was fired at an initial velocity of $21 \text{ m}\cdot\text{s}^{-1}$, giving subjects approximately 400 ms to intercept the ball before it reached their head. When the subject was ready, the examiner first notified subjects that the cannon was "armed." A computer was programmed to fire the foam ball after a randomized delay interval ranging from 2 to 5 s after the cannon was "armed." Subjects blocked the foam balls using both hands. Subjects were given four practice trials to familiarize themselves with the protocol before data were collected for eight trials. To improve accuracy, a sabot was used to transport the foam ball down the cannon barrel without spinning. If the cannon fired inaccurately (>15 cm away from the subject's head), the trial was repeated. To ensure that subjects were being maximally challenged, they were systematically moved closer to the cannon in 60-cm increments after successfully blocking more than five of eight trials at a given distance from the cannon. RT_{sprt} was defined as the elapsed time from the instant the foam ball broke the plane of a light gate (Banner Engineering Corp., Minneapolis, MN) positioned at the barrel of the air cannon until the subject's wrist crossed the horizontal plane at the level of their sternoclavicular joints defined by an optoelectronic marker. The data from the nearest (most challenging) distance from which a subject successfully blocked at least one foam ball were used for analysis.

Kinematic measurements—During RT_{sprt} measurement, optoelectronic markers were placed over the subject's left ulnar styloid process as well as on the chest protector at the level of their sternoclavicular joints. Kinematic data were measured at 1 kHz using an optoelectronic camera system (Optotrak Certus; Northern Digital, Inc., Waterloo, Ontario, Canada). The camera measured the motion of the subject's wrist relative to the horizontal plane of his/her sternoclavicular joints in three dimensions with a resolution of 0.1 mm. The completion of the RT_{sprt} task was defined as the instant the ulnar styloid optoelectronic

marker broke the horizontal plane of the sternoclavicular joints. Optoelectronic and light gate signals were integrated and analyzed using MATLAB (2008b; The MathWorks, Inc., Natick, MA). Any trial for which insufficient cinematic data were collected was discarded. This occurred in only 1.4% of RT_{sprt} trials.

Statistical Analyses

Frequency histograms for RT_{clin} and RT_{sprt} were visually assessed to ensure that the distribution of the data approximated normality. The means of the eight RT_{clin} and RT_{sprt} trials were then calculated for each subject. All data are expressed as mean $\pm$ SD in the text and in Table 1. Correlations between RT_{clin} and RT_{sprt} were calculated using a Pearson correlation coefficient, r . An exploratory analysis was conducted to investigate for gender differences in RT_{clin} and RT_{sprt} using independent sample, two-tailed t -tests. Linear regression was used to assess for age, gender, height, and weight effects on the relationship between RT_{clin} and RT_{sprt}. To assess for a possible learning effect across trials, the mean slopes of the least squares regression lines for RT_{clin} and RT_{sprt} across trials were compared with zero using one-sample t -tests. A slope significantly less than zero would suggest a learning effect over the eight trials. Statistical analyses were conducted using SAS (Version 9.1; SAS Institute Inc., Cary, NC). Figure 3 was generated using Microsoft Excel (Version 10; Microsoft Corp., Redmond, WA).

RESULTS

Twenty-six adult subjects completed the study protocol. Their demographics are summarized in Table 1. Overall, mean RT_{clin} (180 ± 25 ms) was shorter than mean RT_{sprt} (246 ± 27 ms). Males tended to be faster than females for both RT_{clin} and RT_{sprt}; however the difference reached statistical significance only for RT_{sprt} (Table 1). There was a significant positive correlation between RT_{clin} and RT_{sprt} ($r = 0.725$, $P < 0.001$; Fig. 3). RT_{clin} remained a significant predictor for RT_{sprt} when controlling for age, gender, height, and weight using linear regression ($P < 0.001$ for all models examined). No significant learning effects were detected for RT_{clin} or RT_{sprt}: the slopes of the least-squares regression lines were -0.142 ms per trial ($P = 0.787$) for RT_{clin} and -0.146 ms per trial for RT_{sprt} ($P = 0.188$).

DISCUSSION

These results reveal that RT_{clin} is strongly correlated with a functional task designed to simulate a natural head-protective response in a sport-related environment. RT_{clin} accounted for $>52\%$ of the observed variability in the sport-related protective response. We are unaware of any other clinical test that has been shown to be predictive of the ability to protect one's head in an athletic environment. Although the head-protective response used in this study most closely simulates a protective response that might be used by a fielder or pitcher/bowler at close hold in a batted ball sport like baseball, softball, or cricket, we believe that the response has relevance in other sport environments and situations as well. Raising the upper limbs to protect the head and face is a vital protective strategy for avoiding head impacts with other potentially injurious objects encountered during sport participation including other athletes (intentional or unintentional contact with opponents or

teammates) and various components of the playing surface (goal posts, boards, the court, field turf, mat, ice, etc.).

The strong association between RT_{clin} and the ability to protect the head is relevant when considering the potential role for RT_{clin} as a sport concussion management tool. Taken with our previous work demonstrating the measure's reliability and validity (12), its feasibility for use in the training room environment (14), and its sensitivity to the known effect of concussion on reaction time (13), the results of this study support the potential use of RT_{clin} as part of the sports medicine clinician's multifaceted concussion assessment battery. Not only does RT_{clin} seem to represent a simple marker of concussion but also these results show that it is predictive of an athlete's ability to perform a functional head-protective maneuver. Although the use of reaction time as part of a concussion evaluation is not novel, current reaction time assessment methods rely on computers running specialized software. This simple clinical tool seems to hold advantages over currently available methods. Among these are its portability and ease of use, which allow application on the sideline or in the training room. Second is its low cost of a few US dollars, which compares favorably with the costs associated with currently available computerized neuropsychological tests. Such programs are typically associated with software costs of around \$500 per team and accounting for the additional costs of computer hardware and maintenance have been estimated as high as \$669–\$677 per athlete (16). A third advantage, based on subjective impression and observational data, is that RT_{clin} seems to be more intrinsically motivating than a computer-based reaction time measure (14). The final, and possibly most important, advantage of RT_{clin} is its newly identified correlation with a functional response to protect the head.

All established computerized concussion tests incorporate multiple cognitive domains and are not limited to the assessment of simple reaction time. For this reason, we do not propose that RT_{clin} replace computerized neuropsychological test batteries in those athletes who have access to them. Furthermore, we do not propose that RT_{clin} , or any single test for that matter, be used as a stand-alone test for concussion. However, we do submit that RT_{clin} has the potential to become a valuable tool that, when combined with other concussion assessment methods and sound clinical judgment, may improve the sports medicine practitioner's ability to evaluate and treat concussion. Analogous to a stethoscope or a reflex hammer, this tool allows the clinician to extend his/her physical examination. We anticipate that RT_{clin} will have the greatest utility during initial sideline or training room concussion assessment where computerized reaction time testing is impractical and in younger athletes whose teams do not routinely have access to computerized test batteries. This is of significance because the greatest incidence of sport-related concussion occurs in the 10- to 14-yr age group and 65% of emergency department visits for sport-related concussion occur in persons aged 5–18 yr (7).

Our secondary analysis demonstrates faster reaction times for males than females, with the difference reaching statistical significance for RT_{sprt} but not for RT_{clin} . This finding corroborates earlier reaction time studies in athletes (1,10). No learning effect was present for RT_{clin} or RT_{sprt} in this study. Our prior work involving RT_{clin} has shown mixed results with respect to the presence of a learning effect (12,14). This study protocol used four

practice trials before data collection, whereas our prior studies used two practice trials. The additional two practice trials may be responsible for the lack of a learning effect in this study, although this area needs further evaluation.

This study has several limitations. Although all participants were healthy adult volunteers, a formal association with an athletic team or sport was not required for inclusion, so every participant cannot be strictly classified as an athlete. Furthermore, no children or concussed individuals were included in this study. We can think of no reason that the observed correlation between RT_{clin} and RT_{sprt} would not apply to a pediatric population or to athletes after concussion, but this remains to be demonstrated. Another limitation is that the sport-protective response is an artificial simulation of a true sport environment and, as mentioned above, is most specific to a protective reaction that would be used in a batted-ball sport. This was necessary to allow for safe and controlled laboratory data collection, and again this was felt relevant to the use of the hands to protect the head in other athletic environments. A third limitation is that the initiating cue for RT_{clin} and RT_{sprt} differed. RT_{clin} uses a purely visual start cue, namely, the initiation of fall of the device. The start cue for RT_{sprt} was both visual (seeing the foam ball leave the barrel of the air cannon) and auditory (hearing the rush of air associated with firing of the air cannon). When a microphone was placed on the subject's helmet, we found that the sound of the air cannon firing reached the microphone 12 ms before the ball crossing the light gate at the barrel of the air cannon. This difference was consistent across trials and subjects; therefore, it does not affect the overall correlation between RT_{clin} and RT_{sprt} . A final limitation is that RT_{clin} and RT_{sprt} were measured using different techniques. RT_{clin} is based on the distance the apparatus falls before being caught and is subject to measurement bias if the device slides through the subject's fingers before fully stopping. In contrast, RT_{sprt} is defined by the passage of an optoelectronic marker through a virtual plane and has no such bias associated with its measurement. Our subjective experience during data collection was that slippage of the apparatus was minimal. Furthermore, if used in a clinical setting in which preseason baseline RT_{clin} data were compared with postconcussion RT_{clin} data, similar measurement bias would be present in both situations and would be unlikely to significantly alter comparisons.

In conclusion, the findings of the present study indicate that RT_{clin} is predictive of a functional sport-related head-protective response. This finding is novel and significant given that the primary goal of the return-to-play decision-making process is to determine when an athlete is safe to resume competition. These results further support a wider body of work demonstrating the potential value of RT_{clin} as part of the sports medicine practitioner's concussion assessment "tool box." Further study is warranted to better define the role of RT_{clin} in sport concussion assessment.

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FIGURE 1.
The clinical reaction time apparatus. A, Wide-angle view of the device. B, Simulated predrop hand positioning. C, Simulated postcatch hand positioning.

FIGURE 2.

The functional sport-relevant head-protective maneuver. A, Starting position. B, End position. Completion of the RT_{spt} task is defined as the time point when the optoelectronic marker affixed to the subject's left ulnar styloid process crosses the virtual horizontal plane defined by a second optoelectronic marker affixed to the chest protector at the level of the subject's sternoclavicular joint.

FIGURE 3.
Sport-protective reaction time versus clinical reaction time with superimposed linear trend for combined male and female data.

TABLE 1

Subject demographics and reaction time results by gender.

Characteristic	Males	Females
<i>N</i>	13	13
Age (yr)	26.1 ± 8.6	27.8 ± 7.8
Height (cm)	178.0 ± 6.5	168.6 ± 6.5
Weight (kg)	77.6 ± 8.5	69.7 ± 12.1
Mean RT _{clin} (ms)	175 ± 20 ^a	185 ± 28 ^a
Mean RT _{sprt} (ms)	236 ± 28 ^b	257 ± 22 ^b

^a*P* = 0.305.^b*P* = 0.038.