Laboratory Assessment of a Headband-Mounted Sensor for Measurement of Head Impact Rotational Kinematics

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Head impact sensors measure head kinematics in sports, and sensor accuracy is crucial for investigating the potential link between repetitive head loading and clinical outcomes. Many validation studies mount sensors to human head surrogates and compare kinematic measures during loading from a linear impactor. These studies are often unable to distinguish intrinsic instrumentation limitations from variability caused by sensor coupling. The aim of the current study was to evaluate intrinsic sensor error in angular velocity in the absence of coupling error for a common head impact sensor. Two Triax SIM-G sensors were rigidly attached to a preclinical rotational injury device and subjected to rotational events to assess sensor reproducibility and accuracy. Peak angular velocities between the SIM-G sensors paired for each test were correlated ($R^2 > 0.99$, $y = 1.00x$, $p < 0.001$). SIM-G peak angular velocity correlated with the reference ($R^2 = 0.96$, $y = 0.82x$, $p < 0.001$); however, SIM-G underestimated the magnitude by 15.0% ± 1.7% ($p < 0.001$). SIM-G angular velocity rise time (5% to 100% of peak) correlated with the reference ($R^2 = 0.97$, $y = 1.06x$, $p < 0.001$) but exhibited a slower fall time (100% to 5% of peak) by 9.0 ± 3.7 ms ($p < 0.001$). Assessing sensor performance when rigidly coupled is a crucial first step to interpret on-field SIM-G rotational kinematic data. Further testing in increasing biofidelic conditions is needed to fully characterize error from other sources, such as coupling.
[DOI: 10.1115/1.4048574]

1 Introduction

Head kinematic sensors provide the opportunity to measure head impact frequency and severity in sport to study the effects of repetitive head loading and to calculate concussive injury risk based on head kinematic (linear acceleration, angular velocity, and angular acceleration) data [1,2]. It is often assumed the sensor accurately measures ground truth skull motion. However, sensor validation requires a multistep process that assesses intrinsic sensor error (i.e., in a rigidly coupled setup), coupling error (i.e., impact testing on human headform surrogates), and false-positive and -negative rate in live sport (i.e., video review of sensor reported events). Sensors are typically tested in the laboratory using an anthropomorphic test device (ATD) headform struck by a linear impactor [3–6]. Peak kinematic measurements of headband-, helmet-, and mouthguard-mounted sensors are compared to internal headform reference sensors, for which most sensors have high systematic error of up to 35% [3,4,7–11]. Sensor coupling method (e.g., mouthguard versus headband) affects accuracy due to motion of the sensor relative to the skull during impacts; however, error measured in headform validation studies is an indistinguishable combination of coupling and intrinsic electronics error. The aim of the current study was to evaluate intrinsic error in the absence of coupling error and examine the reproducibility and accuracy of a common head impact sensor used for nonhelmeted sports, the Triax Technologies Smart Impact Monitor (SIM-G, Triax Technologies, Inc., Norwalk, CT), using a pure rotational loading device. Rigid attachment during a

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Manuscript received March 17, 2020; final manuscript received August 31, 2020; published online November 12, 2020. Assoc. Editor: Tamara Reid Bush.

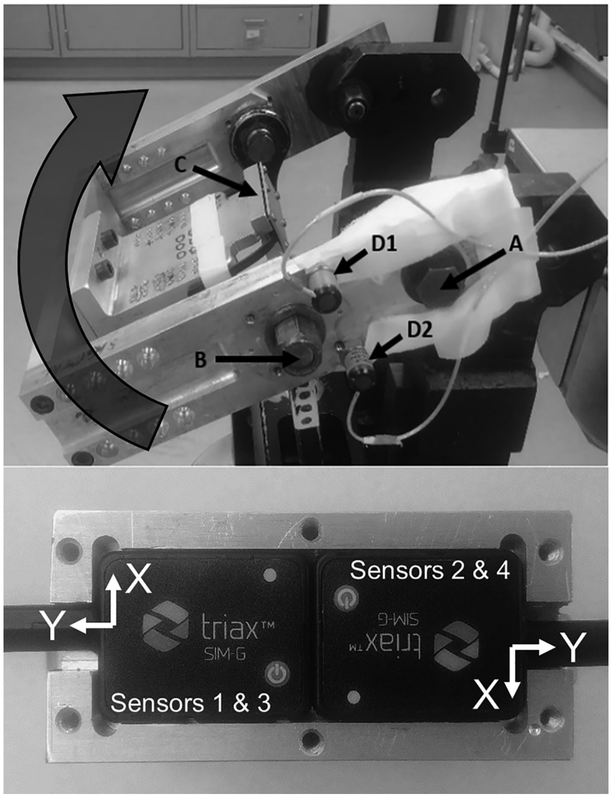

Fig. 1 Experimental setup for testing SIM-G accuracy in pure rotation. (Top) The center of rotation and push rod attachment bolts are indicated by arrows (A and B), respectively. SIM-G sensors were secured as indicated by the arrow C. Magnetohydrodynamic sensors (D1 and D2) provide the reference angular velocity of the HYGE. (Bottom) A custom aluminum casing created a press fit in two axes (*XY* plane) for two SIM-G sensors, allowing intersensor reproducibility to be tested. The last degree-of-freedom (*Z* axis) is secured by a screw tightened top.

controlled rotational event provided a unique method to assess sensor error without the influence of coupling error. This study provides the first step of sensor accuracy evaluation that contributes to interpretation of on-field head rotational kinematics in live contact sports.

2 Materials and Methods

2.1 SIM-G Head Impact Sensor. The Triax SIM-G is composed of a triaxial accelerometer and gyroscope to measure linear acceleration and angular velocity, respectively. The sensor is secured to the back of the head by means of a neoprene headband [5]. The sensor measures linear acceleration from 3 to 150 g but only triggers a recording when a linear acceleration threshold of 16 g is surpassed. The sensor records 62 ms of data at 1000 Hz, 10 ms before and 52 ms after linear acceleration exceeds the threshold [5]. When linear acceleration remains above the threshold beyond 62 ms, a second data file is created and can be time-aligned and combined for analysis. In this study, Triax's proprietary algorithm to remove sensor-recorded events with linear and angular kinematic characteristics atypical of head impacts was turned off to ensure all data was available for analysis.

2.2 HYGE Rotational Motion Device. Two SIM-G sensors, without the headband, were concurrently attached to an adapted HYGE, Inc. (Kittanning, PA) pneumatic linear actuator device that converts linear actuation to pure angular motion (Fig. 1), previously used to induce an impulsive, nonimpact rotational traumatic brain injury in a porcine model [12–14]. Four SIM-G sensors were tested in two sensor pairs (1 versus 2; 3 versus 4) with sensors 1 and 3 depicted on the left in Fig. 1 and sensors 2 and 4 on the right. From Fig. 1, the push rod (B) drives a pulsed, rapid rotation about the stationary point (A) to smoothly rotate the SIM-G sensors (C), creating an angular velocity profile of a head loading event. The HYGE created rotation about the SIM-G *y*-axis equivalent to a frontal head impact. While no impact occurs in this test method, the rotational kinematics mimic the angular kinematics seen in actual sporting head impacts.

Two ARS-06 magnetohydrodynamic (MHD) angular velocity sensors (Applied Technology Associates, Albuquerque, NM) were attached to the sidearm linkage as the reference sensors (D1 and D2) [15]. Raw data were collected at 10 kHz. The average of the MHD sensors was used as the reference angular velocity for comparison.

2.3 Test Matrix. SIM-G sensors were subjected to at least four rotational events at five peak angular velocities driven by gas pressure input (Table 1). A target peak velocity range of 10–35 rad/s was chosen as it represents typical head impacts observed in live sports [16–20]. The HYGE produces a repeatable rotation angle (38.8 ± 1.8 deg) across all angular velocities, resulting in a range of event durations (35–87 ms). Event start and end time points were defined as the time at which the kinematics were 5% of peak angular velocity.

2.4 Data Analysis and Statistics. Key event characteristics include peak angular velocity (i.e., maximum velocity during event), rise time (i.e., time for angular velocity to reach peak velocity from event start at velocity surpassing 5% of peak), fall time (i.e., time from peak velocity to 5% of the peak), and a proxy for average angular acceleration (i.e., approximated by taking the ratio of peak angular velocity and the rise time). Reproducibility was assessed by correlation analysis (Pearson correlation) and paired *t*-test of peak angular velocity, rise time, and fall time comparing responses from the two SIM-G sensors from the same trial. SIM-G intrinsic error was assessed by correlation analysis and paired *t*-tests of peak angular velocity, rise time, fall time, and average angular acceleration comparing SIM-G to HYGE reference values. A significance level of 0.05 was used throughout.

3 Results

A total of 55 tests (with two SIM-G sensors per test) across five angular velocities were conducted. The means and standard deviations of HYGE peak angular velocity loading conditions for the five magnitude groups were: 13.6 ± 0.5, 20.9 ± 0.9, 25.0 ± 0.8, 31.7 ± 0.7, and 37.9 ± 2.1 rad/s. Exemplar angular velocity time

Table 1 Test matrix for each sensor pair and peak angular velocity (load/set pressure ratio)

	Angular velocity magnitude: provided as load/set pressure ratio (PSI)				
Sensor group	25/5	40/8	50/10	75/15	100/20
1 and 2	6 trials	4	8	4	8
3 and 4	4	4	9	4	4

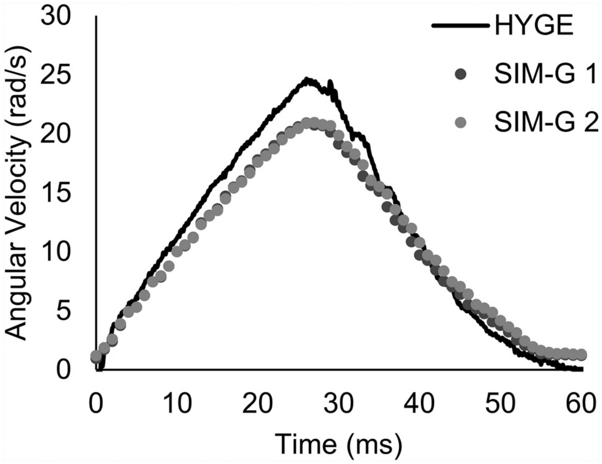

Fig. 2 A representative trace of HYGE and SIM-G angular velocity from a single trial. Traces were time aligned based on event start, defined as the time at which angular velocity was equivalent to 5% of maximum velocity.

series of the HYGE MHD reference and the paired SIM-G sensors for a single test are shown in Fig. 2.

Out of 110 potential recordings (55 trials × 2 sensors), one SIM-G sensor in one trial did not record data. Data from this trial were excluded from analysis. Of the remaining 108 sensor events, 71 (66%) captured the full time series, so both rise time and fall time could be calculated. Rise time could be calculated for 96 (90%) sensor events and fall time for 72 (67%).

In some trials, it was observed that the output from the SIM-G was clipped at approximately 30 rad/s. A positive single axis maximum of 28.9 rad/s and negative single axis absolute maximum of 29.1 rad/s were determined. One trial was removed from analysis because this maximum angular velocity measurement was sustained for more than five consecutive data points.

Reproducibility: Comparison Between SIM-G Sensors. Peak angular velocities between the SIM-G sensors paired for each test were highly correlated (Fig. 3; $R^2 > 0.99$, $y = 1.00x$, $p < 0.001$, $n = 53$ trials); however, magnitudes differed as the sensors with negative y-axis rotation (sensors 2 and 4) consistently

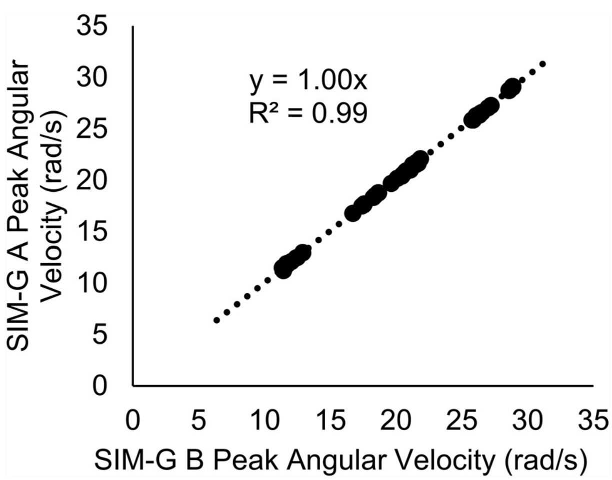

Fig. 3 Measurement of peak angular velocity correlated between SIM-G sensors when subjected to the same rotational event (R^2 > 0.99, $y = 1.00x$, $p < 0.001$, $n = 2$ pairs of sensors across 53 trials). SIM-G A denotes SIM-G sensors 1 and 3 while B denotes sensors 2 and 4. The intercept was set to zero for linear regression.

recorded a slightly higher absolute peak angular velocity (mean difference of 0.10 ± 0.10 rad/s (0.5%), $p < 0.001$). Rise time and fall time showed similar trends as both were correlated between SIM-G sensors (Rise time: $R^2 = 0.98$, $y = 1.02x$, $p < 0.001$, $n = 46$ trials; fall time: $R^2 = 0.78$, $y = 1.05x$, $p < 0.001$, $n = 28$ trials; data not shown). Rise time (mean difference 0.54 ± 0.96 ms; $p < 0.001$) and fall time (mean difference = 1.68 ± 2.97 ms, $p = 0.005$) differed between paired sensors.

Comparison of SIM-G to HYGE Reference Measures. For comparison to HYGE reference measurements, the average of two SIM-G sensors in each trial was used. In the case of a noncalculable rise or fall time for a given sensor in a trial, singular available data from the other sensor was used.

SIM-G peak angular velocity correlated with the HYGE reference measures (Fig. 4(*a*); $R^2 = 0.97$, $y = 0.82x$, $p < 0.001$, $n = 53$ trials). The evident horizontal trend at approximately 30 rad/s (SIM-G, y-axis) was attributed to clipping due to maximum output velocity of the SIM-G sensors. To evaluate the effect of this behavior, ten trials in which sensor measurement reached the maximum value were removed for analysis, and correlation with the reference measures was stronger ($R^2 > 0.99$, $y = 0.84x$, $p < 0.001$, $n = 43$ trials). From these 43 trials, SIM-G peak angular velocity was significantly less than the reference HYGE, on average, 15.0 ± 1.6% ($p < 0.001$). The ten trials were also removed for subsequent analysis of rise time, fall time, and average angular acceleration.

SIM-G data correlated with HYGE data for rise time (Fig. 4(*b*), $R^2 = 0.97$, $y = 1.06x$, $p < 0.001$, $n = 38$ trials) and fall time (Fig. 4(*c*), $R^2 = 0.64$, $y = 1.31x$, $p < 0.001$, $n = 32$ trials). SIM-G had slightly higher rise times compared to the reference HYGE (average difference of 1.5 ± 1.1 ms (6%), $p < 0.001$) and consistently longer fall times [average difference of 9.0 ± 3.7 ms (32%), $p < 0.001$].

SIM-G average angular acceleration correlated with the HYGE (Fig. 5, $R^2 = 0.99$, $y = 0.79x$, $p < 0.001$, $n = 38$ trials); SIM-G had significantly lower average angular acceleration than the reference HYGE [average difference of 203.9 ± 100.3 rad/s^2 (20%), $p < 0.001$].

4 Discussion

Intersensor reproducibility is crucial for comparing head impact kinematic data across players, teams, sports, and genders. SIM-G sensors were highly reproducible; independent SIM-G angular velocity measurement had average peak differences of 0.1 rad/s (0.5%) when simultaneously subjected to the same rotational impulse event. These differences are acceptable for measuring mean head impact angular velocities of approximately 20 rad/s observed in live sports [16–20]. Similarly, rise time differences between sensors are small (0.5 ms) and are potentially attributable to the maximum resolution (1 ms) of the SIM-G sensor. Fall time was still correlated but had higher variability and slightly larger average differences between sensors (1.7 ms). The SIM-G also reliably recorded rotational events with 109 events recorded from 110 possible events. The SIM-G has previously shown high reliability in human head surrogate studies for event recording (86%) [21] and for peak kinematic measurement consistency (Cronbach's alpha > 0.95) [22]. Consistent performance across SIM-G sensors supports the ability to compare head impact kinematics across individual players and teams; however, further testing is needed to assess possible variability introduced by head size and sensor placement.

For analysis of SIM-G intrinsic sensor error, the SIM-G was strongly correlated with the reference but consistently underestimated the peak value by approximately 15%. For peak angular velocity correlation, this study had similar variability to rigidly coupled sensor testing studies [3,23] and lower variability compared to human head surrogate validation studies [9,11,22,24,25]. Specifically, Tyson et al. found an underestimation of angular

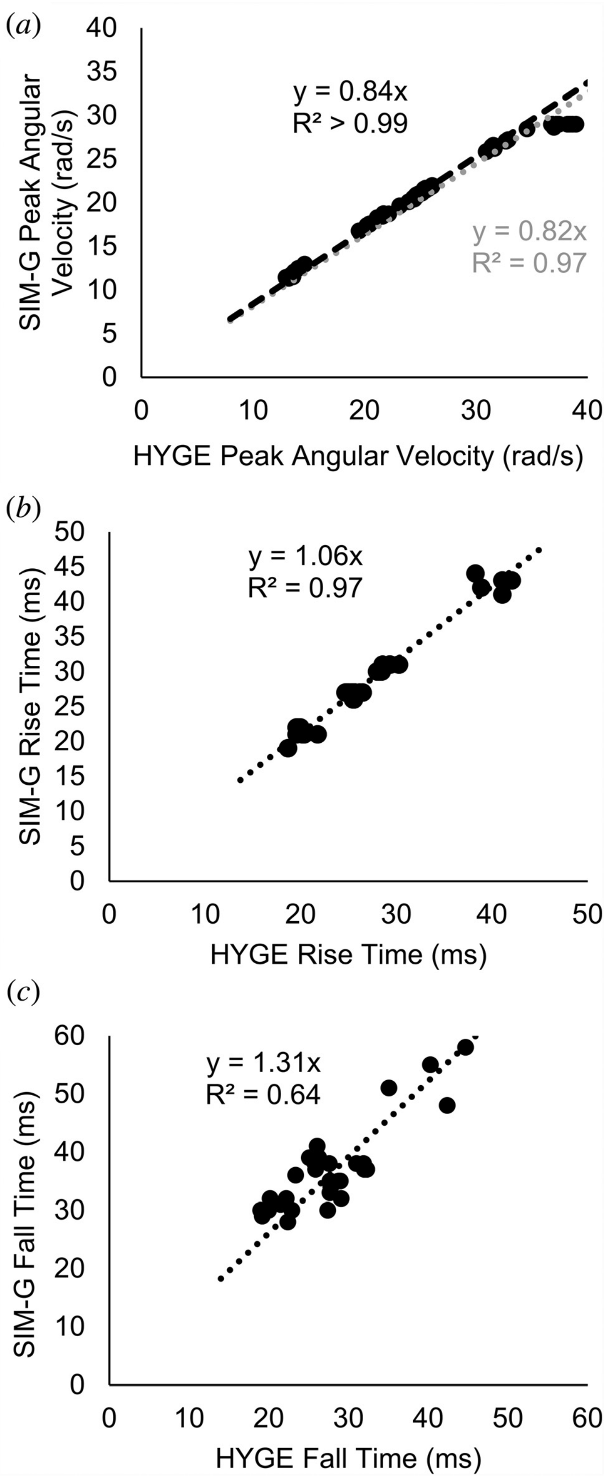

Fig. 4 (*a*) SIM-G peak angular velocities correlated with peak HYGE reference measurements (gray dotted line; R^2 = 0.97, $y = 0.82x$, $p < 0.001$, $n = 53$ trials). Trials in which the SIM-G maximum was reached were removed, increasing the correlation (black dashed line, $R^2 > 0.99$, $y = 0.84x$, $p < 0.001$, $n = 43$ trials). (*b*) SIM-G rise time values correlated with HYGE rise time (R^2 = 0.97, $y = 1.06x$, $p < 0.001$, $n = 38$ trials). (*c*) SIM-G had consistently longer fall times than the HYGE reference (R^2 = 0.64, $y = 1.31x$, $p < 0.001$, $n = 32$ trials).

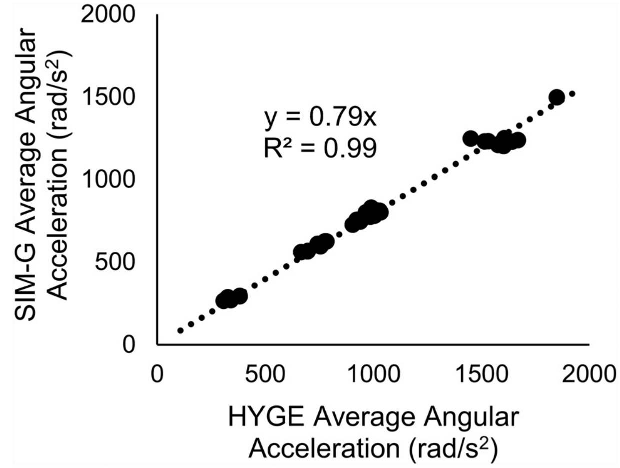

Fig. 5 Average angular acceleration correlated between SIM-G sensors when subjected to the same rotational event (R^2 = 0.99, $y = 0.79x$, $p < 0.001$, $n = 38$ trials), and SIM-G had significantly lower average angular acceleration than the reference HYGE ($p < 0.001$)

velocity when the SIM-G was headband-coupled to a human surrogate headform during linear impactor loading (i.e., slope of peak angular velocity compared to the reference = 0.74–0.94) [9]. Compared to the current study, Tyson et al. found increased error and variability likely introduced by imperfect coupling to the headform and variability in impact location [9]. The current study demonstrated that SIM-G sensors accurately captured the rise time of angular velocity with a difference of less than 2 ms. This relatively small variability is likely introduced by the difference in time resolution for the sensors (10 kHz HYGE versus 1 kHz SIM-G). SIM-G had significantly longer fall times compared to the reference (9 ms on average). These results suggest rise time may provide a more consistent time-based impact characteristic for the SIM-G. The start of an impact has a more rapid rise making it easier to detect, and Wu et al. found that a skullcap mounted sensor displacement from the head increased with time [16].

Angular acceleration is not measured directly by the HYGE or SIM-G devices, and errors are associated with numerical differentiation of gyroscopic impact data [26]. The filtering and derivation of angular acceleration by the SIM-G device is proprietary, and as such, angular acceleration cannot be similarly processed from the HYGE angular velocity for comparison with the SIM-G data. However, peak angular acceleration is a commonly applied metric for describing on-field head impact kinematics [7,27] and predicting brain injury [15]. Therefore, an approximation of average angular acceleration of the rising angular velocity was assessed. Similar to angular velocity, the SIM-G underestimated average angular acceleration by approximately 20% compared to the HYGE reference. Similarly, Tyson et al. reported the SIM-G underestimated angular acceleration by 35% in helmeted and bare head impacts; however, peak angular acceleration had higher variability than angular velocity, introduced by numerical derivation [9].

This study found a maximum sensor measurement capability of approximately 30 rad/s for single axis angular velocity. Recent studies using an in-ear and headband-mounted head impact sensors found that on-field soccer heading frequently produces peak angular velocities greater than 30 rad/s [7,18], and reconstruction of head impact kinematics of alpine skiing crashes had an average peak angular velocity of 43 rad/s [19]. Furthermore, a previous investigation found that the SIM-G did not produce linear acceleration measurements consistent with headform reference sensors when subjected to impacts higher than 80 g [22]. These findings emphasize the need for an expanded range of measurement capability to capture the full extent of higher intensity impacts in sports.

The current study has limitations pertaining to scope, impact event design, and axis testing. First, the current study only investigated angular kinematics because this study leveraged an existing rotational injury device which only measures angular velocity directly. Further, SIM-G automatically transforms linear acceleration to a theoretical center of gravity of the head. The mathematical errors introduced by derivation and transformation to the head center of gravity compound the intrinsic error, of which the isolation was the goal of this study. Second, the sensor was evaluated in a single axis. The specifications of the three axes for the SIM-G angular rate sensor do not differ from one another; therefore, there is no reason to believe other axes would differ from the one tested. Third, the HYGE device created pure rotational events that are representative of angular velocity peak and duration in American football and soccer heading [10,16,28] but longer than typical helmet-to-helmet impact durations measured by linear acceleration in football (8–12 ms) [27,29]. Additional short duration impact testing is needed to assess the bandwidth and sample rate limitations of the SIM-G that may affect accuracy of measurement of specific impact types (i.e., head-to-ground) in on-field kinematics [30]. Fourth, production of the SIM-G has been discontinued by Triax. However, research using the device has continued, and studies using the device in live sport continue to be published. Assessing the SIM-G error is necessary to interpret research using the SIM-G in live sport.

In summary, quantifying intrinsic SIM-G sensor reproducibility and accuracy provides a crucial first step to interpret head impact kinematic data investigating traumatic brain injury and long-term ramifications of contact sport. In a pure rotational loading environment with rigid coupling, the SIM-G was highly reproducible and strongly correlated with reference measures for peak angular velocity. The SIM-G, however, consistently underestimated velocity magnitude by approximately 15%. Further research is needed on coupling error and false positive and false negative to fully characterize SIM-G accuracy and performance.

Acknowledgment

Research reported in this publication was supported by National Institute of Neurologic Disorders and Stroke of the National Institutes of Health under award number R01NS097549 and the Pennsylvania Department of Health. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health and the Pennsylvania Department of Health.

Funding Data

- National Institute of Neurological Disorders and Stroke (No. R01NS097549; Funder ID: 10.13039/100000065).
- Pennsylvania Department of Health (CURE Grant; Funder ID: 10.13039/100004897).

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