Instrumented balance assessment in mild traumatic brain injury: Normative values and descriptive data for acute, sub-acute and chronic populations

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Abstract

Often the Balance Error Scoring System (BESS) is used to assess balance during a clinical evaluation of a patient presenting with mild Traumatic Brain Injury (mTBI). Although recent research has shown the benefits of using inertial sensor measures such as the Root Mean Square (RMS) of the acceleration in place of clinical scoring, few normative data are available for clinicians to reference. The purpose of this paper was to provide normative data collected using wearable sensors for healthy controls across three age groups, as well as providing cohort data for mTBI participants across three stages following injury (acute, sub-acute and chronic). The RMS in the Medio-Lateral direction (ML RMS sway) of each condition (double stance – DS; single stance – SS; and tandem stance – TS) was extracted per participant for analysis. The average ML RMS sway across all conditions was also calculated (ML RMS-Av). Percentiles were calculated to provide normative data, and two multivariate general linear models were used to evaluate differences between 1) non-athlete controls, athlete controls, and athletes with acute mTBI, and 2) non-athletic cohorts of control, sub-acute and chronic mTBI groups across young, middle-aged, and older adults. Model 1 revealed athletes with acute mTBI had more ML RMS sway than athlete controls for the DS condition \( (p < 0.001) \), but no differences with non-athlete controls. Athlete controls also had less ML RMS sway for the SS condition and ML RMS-Av \( (p \leq 0.022) \) compared with non-athlete controls. Model 2 revealed less ML RMS sway in the control group than the sub-acute and chronic mTBI groups for DS \( (p \leq 0.004) \), but no differences between the sub-acute and chronic group, while more ML RMS sway occurred in the chronic group compared with the control and sub-acute groups for the TS condition and ML RMS-Av \( (p \leq 0.013) \). Older adults had more ML RMS sway than young and middle-aged adults for SS, TS and ML RMS-Av \( (p \leq 0.019) \), while there were no differences between the young and middle-aged adults. Normative values presented here can help increase the practical application of instrumented balance assessment of mTBI patients through wearable sensors. ML RMS sway in the DS condition provided the clearest distinction between control and mTBI groups, but we caution that young adult athletes need to be assessed against athletic peers in the absence of baseline normative values. In non-athlete cohorts, age and gender norms may not be necessary to consider when assessing DS performance; however, age may be an important factor to consider when accessing norms for other stance conditions or the average performance across all conditions.

Keywords

IMU, postural stability, BESS, mild head injury, concussion

Introduction

Imbalance is known to occur after mild Traumatic Brain Injury (mTBI, conventionally also often referred to as concussion). Advances in science and technology

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have been evolving the way we collectively understand and conduct balance assessment in this population: from initial force plate instrumentation,\textsuperscript{1–3} to simplified clinical assessments,\textsuperscript{4,2} and back to instrumented procedures. Recently, the use of inertial sensor research,\textsuperscript{6–11} has been influencing clinical laboratory practices. Seminal works in this field demonstrated the ability to detect postural instability within the first few days after an mTBI.\textsuperscript{1,3} As a result of these findings, they indicated that biomechanically assessing balance using force plates was a reliable and valid way to provide clinicians with objective data, but also recognized that the majority of clinicians do not have access to these technologies.\textsuperscript{1,3} As a consequence, an alternative solution was pursued to provide a clinically accessible tool, and the Balance Error Scoring System (BESS) was created.\textsuperscript{6,5,12} Though now widely used, there are well documented limitations associated with this subjective assessment method.\textsuperscript{6,8,13–20} Consequently, researchers have more recently sought to take advantage of newer technologies such as wearable inertial sensors to re-instrument balance assessment procedures.\textsuperscript{6–11,21,22} Despite these tools being more objective and sensitive to instability,\textsuperscript{11,22} there has been limited application of these devices in applied clinical settings.

Knowledge transfer from research to practical application takes time, and changes (or lack thereof) can be influenced by scientific, social, cultural, and organizational factors.\textsuperscript{23} In mTBI research for example, there was an approximate lag of 7.5 years between early research on computerized balance assessment in mTBI\textsuperscript{1,3} and when the advantages of evaluating balance were identified in the second concussion consensus statement\textsuperscript{24}; balance assessments were not recommended in the first.\textsuperscript{25} Further, the BESS and its abridged version, the modified BESS (mBESS) were identified as the clinical tools in the 3rd,\textsuperscript{26} and 4th\textsuperscript{27} consensus statements and their associated Sports Concussion Assessment Tools (SCAT-2, SCAT-3, and also present in the SCAT-5\textsuperscript{28}). Unsurprisingly, the BESS and the mBESS, are perhaps now the most well-known post-concussion clinical tools for balance assessment. The perserviveness of these methods, may be a result of their representation within the 2nd, 3rd and 4th consensus statements (e.g. social and cultural factors), or due to accessibility, cost-efficiency, and the ease at which these tests can be administered (e.g. organizational). Nonetheless, the need for objective balance assessments is highlighted by the growing body of evidence indicating limitations in clinical assessments (e.g. BESS/mBESS) related to subjectivity, reliability,\textsuperscript{14} validity,\textsuperscript{6,8,15} sensitivity,\textsuperscript{6,8,15} learning,\textsuperscript{16–19} and fatigue effects.\textsuperscript{20}

Released in 2004 and 2014, the position statements by the National Athletic Trainers Association (NATA) identified the BESS as a useful sideline field test used in conjunction with other screening tools, or within the initial days following injury.\textsuperscript{29,30} However, NATA also acknowledged that objective computerized (i.e. instrumented) procedures can more precisely quantify and evaluate imbalance after injury.\textsuperscript{29,30} In fact, studies have shown that instrumented assessments are more sensitive for detecting imbalance, especially subtle impairment, and imbalance that persists beyond the presence of visually identifiable impairment.\textsuperscript{31–34} However, these technologies have typically been limited to use in clinical research settings due to the need for specialized equipment, and technical expertise to administer, analyze, and interpret tests. These scientific complications are an issue belonging to the aforementioned organizational factors. Nonetheless, recent technological advances and increased accessibility has, at least in research, given rise to the opportunity to explore post-mTBI balance impairments using wearable inertial sensors as an alternative to force plates.\textsuperscript{6–11,21,22}

Similar to force plates, wearable inertial sensors are still subject to technical analysis and interpretation factors that can be a barrier to clinical implementation. There are ample biomechanical measures that can be derived from inertial sensors, such as spatial dispersion measures (e.g. sway area, path length, root mean square), spatio-temporal measures (velocity, jerk) and frequency domain measures (e.g. centroidal frequency). The root mean square (RMS) is a measure of spatial dispersion calculated by the square root of the arithmetic mean of the squares of the original values (Formula 1).

\[
x_{\text{rms}} = \sqrt{x_1^2 + x_2^2 + \ldots + x_n^2} \tag{1}
\]

RMS of the acceleration signal of inertial sensors has been shown to be a valid estimator of RMS of force plate center of pressure (\(r = 0.79\) in young adults\textsuperscript{35}; \(r = 0.74\) in older adults\textsuperscript{36}) and to have acceptable retest reliability (\(\text{ICC} = 0.71\) in healthy, \(\text{ICC} = 0.83\) in a neurologic population).\textsuperscript{36} In an mTBI population with persisting symptoms (5 ± 3.3 months post injury), RMS of the acceleration signal collected during the mBESS had significantly better diagnostic accuracy than the non-instrumented BESS and the mBESS error scores.\textsuperscript{8} Furthermore, the mediolateral component of the RMS acceleration (ML RMS sway, mm/s\textsuperscript{5}) has been identified as being the most sensitive to classifying mTBI in an acute population,\textsuperscript{8} and having the potential to detect balance differences throughout the recovery period and after returning to sport.\textsuperscript{9}
Therefore, ML RMS sway may be beneficial to track in a clinical setting.

While trained persons with biomechanics expertise may have the necessary knowledge to currently translate findings, for instrumented testing and ML RMS sway to be used in a clinical setting, information that aids the interpretation of the data is required. Moreover, normative ranges of age-matched healthy persons, and persons who have sustained an mTBI who are at different stages of recovery would be highly beneficial to clinicians and researchers. There are limited studies providing normative ranges for postural sway metrics across the timeline of mTBI compared with healthy controls. Thus, the aim of this paper was to establish normative ranges for healthy controls and explore any differences across populations of acute, sub-acute, and chronic mTBI. Establishing percentile ranges for the instrumented mBESS, specifically for ML RMS sway, could ease the organizational burden of instrumented balance assessments. This could be a preliminary step to clinically implement inertial sensors to aid in the objective identification and categorization of balance deficits in patients after mTBI and inform further rehabilitation and return to play protocols.

Methods
Participants

This manuscript presents a secondary analysis on data collected across four separate studies that measured postural sway in healthy controls and three different mTBI populations who were at different time-points since injury; acute (<4 days), sub-acute (<3 months) and chronic (>3 months). Specifically, the acute population included 50 athletes post-mTBI and 82 matched controls (NCT01661075), the sub-acute population included 58 people post-mTBI (NCT03479541), and the chronic population included 56 mTBI and 61 matched controls (NCT02748109). Participant demographic information can be found in Table 1.

Subjects were recruited from the Portland Metropolitan Area including 6 universities, the Oregon Health & Science University (OHSU) Concussion Clinic, and the local community. Common recruitment criteria included participants 1) being between 18–60 years-old, 2) having a diagnosable mTBI according to VA/DoD criteria having no or minimal cognitive impairments with a score of 0 to 8 on the Short Blessed Test. Common exclusion criteria included participants 1) having another condition that inhibits balance performance (i.e. CNS diseases, stroke, lower extremity amputation, etc.), 2) having partaken in substance-abuse in the past month, according to DSM-V classifications, 3) displaying disorderly behavior hindering the validity and/or safety of study sessions, 4) reporting or displaying significant pain, 5) being a pregnant female due to potential effects on balance, 6) having a history of pathological symptoms that affect the musculoskeletal, peripheral vestibular or ocular motor systems, 7) being unable to refrain from using balance-impairing medication for 24 hours prior to testing session, and 8) a history of brain injury within the past year for the control groups.

Specific populations had further inclusion criteria. All athletes were recruited from Division I, II or III NCAA athletics programs, and were between 18 to 29 years of age. The athletes with acute mTBI were included if they were within 72 hours of their injury, and were available for testing at the athlete’s university. For the sub-acute population, participants had to be within 2–12 weeks post-mTBI, while the chronic population had to be more than 3 months post mTBI. Each of the studies were conducted in accordance with the Declaration of Helsinki (1964), and were approved by the OHSU Institutional Review Board (IRB) and/or the Veterans Affairs (VA) IRB. All participating study subjects received and signed informed consent forms approved by the OHSU IRB.

Data collection

Data collection details for each study have been previously reported. Common demographic details that were collected included participant age (yrs), sex, height (m), mass (kg), and body mass index (BMI). Symptom severity and the total number of symptoms as derived by the second Sports Concussion Assessment Tool (SCAT-2) were also collected during each study. In each study, the instrumented mBESS was conducted as part of a gait and balance test battery. The mBESS involves measurement of balance in three different positions (double stance with feet together [DS], single-leg stance [SS], and tandem stance [TS]) on a firm surface only. Like the BESS, each stance position is conducted with the eyes closed and hands placed on the hips. All subjects wore an Opal sensor (APDM Inc., Portland, OR) placed on the posterior lumbar (L5) region to measure postural sway while performing each of the mBESS trials. In comparison with the standard clinical mBESS procedure, the instrumented mBESS involved each stance position being captured for 30 seconds, rather than 20 seconds. Our rationale for this has been previously published. Procedures for the instrumented mBESS were common across each study, with the exception of: 1) The location where the testing procedure took place for the acute population and their matched controls, participants were tested in a quiet well-lit hallway in their
athletic training facility, while the sub-acute and chronic populations were tested in a quiet clinical room either at OHSU or the VA Portland Oregon Health Care System; and 2) Participants from the acute and chronic groups wore Opal v1 sensors, whereas the participants from the sub-acute group wore the Opal v2 sensor. Data were processed and extracted using Mobility Lab (APDM Inc., Portland, OR). Although different versions of the Opal sensors were used, attachment of the sensor, data collection procedures, data analysis software and data extraction procedures for ML RMS sway were identical. The differences in technical specifications are provided in Supplementary Table 1.

Statistical analyses

Data across the four studies were stratified into mTBI groups (control, sub-acute, and chronic), age cohorts (young-adults 18–29, middle-aged adults 30–44, and older adults 45–60), and an athlete cohort (athlete control and athlete acute mTBI group). Descriptive data, including percentiles for ML RMS sway, were calculated for each of stratum of controls, acute, sub-acute, and chronic mTBI. Normality was then explored across cohorts and the entire sample using a combination of histograms and then Shapiro-Wilk’s tests. As the majority of distributions across the dataset were non-normal, ML RMS sway data were then log transformed for statistical comparison of groups. Due to pooling data from multiple studies and the resulting uneven sampling of athletes in the young-adult and acute-stage mTBI, two multivariate general linear models (GLM) with gender included as a covariate, were used to assess instrumented outcomes between groups. The first model was used to evaluate the differences in young-adult groups (non-athlete controls, athlete controls, and athletes with acute mTBI), and the second model was used to evaluate differences between the control, sub-acute and chronic mTBI groups, as well as age strata (young, middle-aged, and older adults). It should be noted that the healthy controls aged 18–29 years were used in both models as 1) the non-athlete controls, and 2) the young adult control group. Both models tested the four outcome measures, which were ML RMS sway for 1) DS, 2) SS, 3) TS, and 4) the average ML RMS sway across all conditions (ML RMS-Av). Pillai’s trace was used as the test statistic and Levene’s Test was used to evaluate equality of error variance of the dependent variables across

### Table 1. Participant demographic information.

| mTBI | Age (years) | Gender (M/F) | Mass (kg) | Height (m) | BMI (kg/m²) | Time since injury (days) |
|------|-------------|--------------|-----------|------------|-------------|-------------------------|
| Control | Athletes | 18–29 | 82 (2) | 44 (M/38 F) | 80.2 (20.6) | 1.8 (0.1) | 0 (0–15) | 0 (0–18) | 2 (0–20) |
|        | Non-athletes | 18–29 | 20 (2) | 7 (M/13 F) | 70.4 (12.2) | 1.7 (0.1) | 23.9 (3.7) | 0 (0–3) | 0 (0–3) | 2 (0–11) |
|        | 30–44 | 24 (6) | 10 (M/14 F) | 74.3 (20.2) | 1.7 (0.1) | 25.6 (5.3) | 2 (0–9) | 2 (0–9) | 3 (0–14) |
|        | 45–60 | 17 (5) | 8 (M/9 F) | 80.8 (23.2) | 1.7 (0.1) | 26.5 (5.7) | 2 (0–12) | 2 (0–16) | 11 (2–20) |
| Acute | Athlete | 18–29 | 50 (2) | 35 (M/15 F) | 87.4 (20.4) | 1.8 (0.1) | 27.1 (4.5) | 13 (0–22) | 28 (0–89) | 4 (0–13) | 2 (1) |
| Sub-acute | Non-athlete | 18–29 | 28 (4) | 4 (M/24 F) | 72.4 (16.4) | 1.7 (0.1) | 25.6 (6.2) | 20 (13–22) | 65 (16–100) | 4 (0–21) | 29 (18) |
|        | 30–44 | 19 (4) | 4 (M/15 F) | 70.5 (14.1) | 1.7 (0.1) | 25.3 (4.7) | 19 (9–22) | 44 (15–102) | 3 (0–22) | 32 (21) |
|        | 45–60 | 11 (3) | 1 (M/10 F) | 69.6 (11.6) | 1.7 (0.1) | 24.5 (4.6) | 20 (10–22) | 56 (19–83) | 13 (6–20) | 29 (17) |
| Chronic | Non-athlete | 18–29 | 13 (5) | 4 (M/9 F) | 81.2 (14.5) | 1.7 (0.1) | 28.0 (5.8) | 10 (0–22) | 14 (0–48) | 6 (1–20) | 923 (857) |
|        | 30–44 | 28 (4) | 8 (M/20 F) | 89.8 (41.9) | 1.6 (0.3) | 27.5 (5.5) | 16 (0–22) | 34 (0–94) | 10 (0–20) | 966 (1308) |
|        | 45–60 | 15 (3) | 5 (M/10 F) | 77.4 (20.3) | 1.7 (0.1) | 26.0 (5.8) | 18 (6–21) | 45 (6–78) | 12 (0–20) | 688 (666) |

*Age, mass, height, BMI, and time since injury presented as mean (SD). SCAT symptoms, SCAT symptom severity, and mBESS clinical total presented as median (min - max).
groups. The alpha level was set at 0.05, with *post-hoc* analyses Bonferroni corrected for multiple comparisons. Significant covariates were also evaluated post-hoc using independent-samples t-tests. All data were analyzed in SPSS (SPSS Statistics 25, IBM Corporation, Armonk, NY) for analysis.

**Results**

Demographic data for all subjects are provided in Table 1. The acute mTBI population was composed only of young-adult athletes, while the sub-acute and chronic mTBI cohorts consisted of only non-athletes across age strata. Control data were provided for young-adult athletes, as well as non-athletes across age strata. The breakdown of which sports the athlete controls and athletes with acute mTBI participated in, is provided in Table 2. Percentile scores across cohort and age strata are provided in Table 3.

**Comparison of athlete controls, non-athlete controls, and athletes with acute stage mTBI**

Multivariate GLM analysis yielded a significant main effect for group ($F_{(8,326)} = 2.82; p = 0.005, \eta^2 = 0.07$) and age ($F_{(8,326)} = 4.96; p < 0.001, \eta^2 = 0.11$). Gender was found to be significant covariate ($F_{(4,162)} = 7.64; p < 0.001, \eta^2 = 0.16$). Levene’s Test was not significant for ML RMS sway for any of the conditions ($p > 0.05$). ML RMS sway for the DS ($F_{(2,165)} = 8.53; p < 0.001, \eta^2 = 0.09$), TS ($F_{(2,165)} = 4.46; p = 0.013, \eta^2 = 0.05$), and ML RMS-Av ($F_{(2,165)} = 5.60; p = 0.004 \eta^2 = 0.06$) were significant for group. ML RMS sway for the DS ($F_{(2, 165)} = 3.08; p = 0.049, \eta^2 = 0.04$), SS ($F_{(2, 165)} = 5.37; p = 0.006, \eta^2 = 0.06$), TS ($F_{(2,165)} = 13.79; p < 0.001, \eta^2 = 0.14$), and ML RMS-Av ($F_{(2, 165)} = 8.40; p < 0.001, \eta^2 = 0.09$) were significant for age. Gender was a significant covariate for the SS ($F_{(1,165)} = 9.74; p = 0.002, \eta^2 = 0.06$) and ML RMS-Av ($F_{(1,165)} = 9.35; p = 0.003, \eta^2 = 0.05$), with males displaying less ML RMS sway. *Post-hoc* analyses revealed the control group had significantly less ML RMS sway than the sub-acute and chronic mTBI groups for DS ($p = 0.004$ and $p < 0.001$, respectively). There were no significant differences between the sub-acute or chronic groups for DS. For TS and ML RMS-Av sway, there were no differences between the controls and the sub-acute mTBI group. However, the chronic mTBI group had more ML RMS sway than the control and the sub-acute for the TS condition ($p = 0.002$ and $p = 0.013$, respectively) and ML RMS-Av ($p = 0.001$ and $p = 0.01$, respectively). There were no

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**Table 2. Breakdown of sports participation in the athlete control and athlete with acute mTBI groups.**

|                   | Male Control | mTBI | Female Control | mTBI |
|-------------------|--------------|------|----------------|------|
| **Total**         | 44           | 35   | 38             | 15   |
| **Contact sports**|              |      |                |      |
| Football          | 20 (45.5%)   | 32 (91.4%) | –             | –    |
| Soccer            | 5 (11.4%)    | 1 (2.9%)   | 10 (26.3%)    | 8 (53.3%) |
| Basketball        | 1 (2.3%)     | 1 (2.9%)   | 8 (21.1%)     | 2 (13.3%) |
| Lacrosse          | –            | –        | –             | –    |
| **Non-contact**   |              |      |                |      |
| Baseball/softball | 9 (20.5%)    | 1 (2.9%)   | 6 (15.8%)     | 1 (6.7%) |
| Tennis            | 1 (2.3%)     | –        | –             | –    |
| Track and Field   | 8 (18.2%)    | –        | 9 (23.7%)     | 1 (6.7%) |
| Volley ball       | –            | –        | 4 (10.5%)     | 1 (6.7%) |
| Swimming          | –            | –        | 1 (2.6%)      | –    |

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**Comparison of controls, and those in the sub-acute and chronic stages of mTBI**

Multivariate GLM analysis yielded a significant main effect for group ($F_{(8,326)} = 2.82; p = 0.005, \eta^2 = 0.07$) and age ($F_{(8,326)} = 4.96; p < 0.001, \eta^2 = 0.11$). Gender was found to be significant covariate ($F_{(4,162)} = 7.64; p < 0.001, \eta^2 = 0.16$). Levene’s Test was not significant for ML RMS sway for any of the conditions ($p > 0.05$). ML RMS sway for the DS ($F_{(2,165)} = 8.53; p < 0.001, \eta^2 = 0.09$), TS ($F_{(2,165)} = 4.46; p = 0.013, \eta^2 = 0.05$), and ML RMS-Av ($F_{(2,165)} = 5.60; p = 0.004 \eta^2 = 0.06$) were significant for group. ML RMS sway for the DS ($F_{(2, 165)} = 3.08; p = 0.049, \eta^2 = 0.04$), SS ($F_{(2, 165)} = 5.37; p = 0.006, \eta^2 = 0.06$), TS ($F_{(2,165)} = 13.79; p < 0.001, \eta^2 = 0.14$), and ML RMS-Av ($F_{(2, 165)} = 8.40; p < 0.001, \eta^2 = 0.09$) were significant for age. Gender was a significant covariate for the SS ($F_{(1,165)} = 9.74; p = 0.002, \eta^2 = 0.06$) and ML RMS-Av ($F_{(1,165)} = 9.35; p = 0.003, \eta^2 = 0.05$), with males displaying less ML RMS sway. *Post-hoc* analyses revealed the control group had significantly less ML RMS sway than the sub-acute and chronic mTBI groups for DS ($p = 0.004$ and $p < 0.001$, respectively). There were no significant differences between the sub-acute or chronic groups for DS. For TS and ML RMS-Av sway, there were no differences between the controls and the sub-acute mTBI group. However, the chronic mTBI group had more ML RMS sway than the control and the sub-acute for the TS condition ($p = 0.002$ and $p = 0.013$, respectively) and ML RMS-Av ($p = 0.001$ and $p = 0.01$, respectively). There were no
significant differences in ML RMS sway between age groups noted for DS after Bonferroni correction for multiple comparisons. For SS, TS, and ML RMS-Av, the older adults had more ML RMS sway than the young adults (SS: \( p = 0.004 \); TS: \( p < 0.001 \); ML RMS-Av: \( p < 0.001 \)) and the middle-aged adults (SS: \( p = 0.019 \); TS: \( p = 0.001 \); ML RMS-Av: \( p = 0.003 \)). There were no significant differences

Table 3. ML RMS sway percentiles per cohort and age strata, presented at mm/s².

|                | DS       | SS       | TS       | ML RMS-Av |
|----------------|----------|----------|----------|-----------|
|                | 10th     | 25th     | 50th     | 75th      | 90th      | 10th     | 25th     | 50th     | 75th      | 90th      | 10th     | 25th     | 50th     | 75th      | 90th      |
| Controls       |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| Athletes       |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| 18–29          | 32       | 38       | 47       | 58        | 77        | 105      | 173      | 243       | 384       | 586       | 66       | 82       | 129      | 212       | 294       | 85       | 109      | 151      | 210       | 292       |
| Non-athletes   |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| 18–29          | 35       | 43       | 65       | 71        | 81        | 185      | 258      | 427       | 582       | 881       | 72       | 102      | 129      | 160       | 343       | 100      | 146      | 216      | 329       | 385       |
| 30–44          | 29       | 34       | 47       | 55        | 77        | 155      | 242      | 347       | 466       | 1000      | 87       | 115      | 156      | 196       | 329       | 110      | 139      | 176      | 245       | 445       |
| 45–60          | 43       | 48       | 53       | 64        | 86        | 332      | 462      | 591       | 939       | 1084      | 193      | 240      | 363      | 534       | 703       | 217      | 248      | 346      | 495       | 619       |
| mTBI Acute     |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| Athletes       |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| 18–29          | 32       | 38       | 47       | 58        | 77        | 105      | 173      | 243       | 384       | 586       | 66       | 82       | 129      | 212       | 294       | 85       | 109      | 151      | 210       | 292       |
| Non-athletes   |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| 18–29          | 35       | 43       | 65       | 71        | 81        | 185      | 258      | 427       | 582       | 881       | 72       | 102      | 129      | 160       | 343       | 100      | 146      | 216      | 329       | 385       |
| 30–44          | 29       | 34       | 47       | 55        | 77        | 155      | 242      | 347       | 466       | 1000      | 87       | 115      | 156      | 196       | 329       | 110      | 139      | 176      | 245       | 445       |
| 45–60          | 43       | 48       | 53       | 64        | 86        | 332      | 462      | 591       | 939       | 1084      | 193      | 240      | 363      | 534       | 703       | 217      | 248      | 346      | 495       | 619       |
| mTBI Sub-acute |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| Athletes       |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| 18–29          | 32       | 38       | 47       | 58        | 77        | 105      | 173      | 243       | 384       | 586       | 66       | 82       | 129      | 212       | 294       | 85       | 109      | 151      | 210       | 292       |
| Non-athletes   |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| 18–29          | 35       | 43       | 65       | 71        | 81        | 185      | 258      | 427       | 582       | 881       | 72       | 102      | 129      | 160       | 343       | 100      | 146      | 216      | 329       | 385       |
| 30–44          | 29       | 34       | 47       | 55        | 77        | 155      | 242      | 347       | 466       | 1000      | 87       | 115      | 156      | 196       | 329       | 110      | 139      | 176      | 245       | 445       |
| 45–60          | 43       | 48       | 53       | 64        | 86        | 332      | 462      | 591       | 939       | 1084      | 193      | 240      | 363      | 534       | 703       | 217      | 248      | 346      | 495       | 619       |
| Chronic        |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| Non-athletes   |          |          |          |           |           |          |          |           |           |           |          |          |           |           |           |
| 18–29          | 32       | 38       | 47       | 58        | 77        | 105      | 173      | 243       | 384       | 586       | 66       | 82       | 129      | 212       | 294       | 85       | 109      | 151      | 210       | 292       |
| 30–44          | 38       | 48       | 66       | 90        | 154       | 244      | 280      | 707       | 1126      | 1279      | 93       | 140      | 310      | 547       | 752       | 139      | 218      | 392      | 486       | 730       |
| 45–60          | 45       | 64       | 79       | 93        | 116       | 232      | 452      | 564       | 733       | 999       | 133      | 247      | 403      | 486       | 603       | 177      | 275      | 343      | 397       | 560       |

Figure 1. Box plots sub-plotted for ML RMS sway per condition for non-athlete controls, athlete controls and the athlete acute-mTBI group: (A) Double support – DS; (B) Single-leg support – SS; (C) Tandem support – TS; (D) Average across conditions – ML RMS-Av.
between young adults and middle-aged adults. ML RMS sway per cohort and age group are visualized in Figure 2 for each of the conditions.

**Discussion**

Increased sensitivity and objectivity have been named as advantages to using instrumented approaches to assess balance. Specifically, increased data resolution in instrumented balance assessments allows for the subtle corrections associated with maintaining balance to be detected, while objectivity reduces the reliance on the clinician to detect subtle impairments. One of the main limitations of instrumenting clinical procedures is garnering meaning from the quantitative data produced. To help translate knowledge into clinical settings, we collated data from four studies, which each collected instrumented sway data during the mBESS, thereby using the same commonly used clinical methodology to provide normative data for ML RMS sway. This measure quantifies spatial dispersion of the sway trajectory in the mediolateral direction (coronal plane). To the authors’ knowledge, this is the first study to provide normative sway data across 1) young adult athlete (acute mTBI and control) and non-athletes (controls), and 2) three age groups (18–60) for different mTBI cohorts (sub-acute, and chronic) as well as healthy controls. The provision of percentiles in this paper afford references to be made against the provided populations to aid clinicians in interpreting the instrumented mBESS when individual baseline values for these tests are unavailable for comparison.

As availability of wearable sensors and similar systems (e.g. phone applications) increases, one limitation is that several commercial products do not disclose the calculations associated with their ‘sway measurements’. We believe that it is important for the end user to have confidence in, and understand the metric being calculated and reported. The benefit of ML RMS sway is that it can easily be calculated from raw acceleration data, and in some cases, inertial sensor systems will directly output this measure, making its use more widely interpretable.

**Comparison of athlete controls, non-athlete controls, and athletes with acute stage mTBI**

In the DS condition, the athlete control group had the least ML RMS sway, which was notably different to the athlete acute mTBI group. Comparatively, the non-athlete control group did not perform better than the acute mTBI group, or worse than the athlete controls. Although we have already identified and published on the presence of differences between healthy athlete controls and athletes in the acute stage of mTBI, the lack of difference found between the non-athlete controls and the athlete acute mTBI group provides an important consideration for clinicians. Given only significant
differences were revealed between athlete controls and the athlete acute mTBI group suggests the need to consider athletes only in reference to other athletes, rather than draw any conclusions from non-athlete healthy control data.

Evaluation of the performance on the SS condition, and resulting ML RMS-Av sway revealed somewhat intuitive results; there was no difference between athlete-controls and the athlete acute-mTBI group, yet the athlete controls displayed less ML RMS sway than the non-athlete controls for the SS condition and the ML RMS-Av. Firstly, the lack of difference between the athlete controls and the athlete acute mTBI group is plausible, given the increased task difficulty of the SS condition, and may be attributed to the increased variability in performance of this stance condition in the non-concussed state. Nonetheless, it is interesting that this increased task difficulty did not wash out the difference between the athlete controls and the non-athlete controls. It is conceivable that athletes would have increased balance control in comparison to non-athletes during single-leg stance positions. Of note, the mBESS SS condition requires the participant to stand on the non-dominant leg, yet, in clinical settings leg dominance is most often determined by the preferred: 1) leg used to kick a ball, 2) leg to first step up a stair, or 3) handedness of the participant. In each of these cases, the preferred leg (or hand), may not in fact represent the dominant leg when referring to strength or stability. As a result, the determined leg to stand on in this condition may end up being the more stable in the athlete population – giving an added advantage over their non-athlete counterparts who may not be as reliant on single leg stability throughout their daily activities.

Comparison of controls, and those in the sub-acute and chronic stages of mTBI

Less ML RMS sway was found in the control group compared with the sub-acute and chronic mTBI groups completing the DS condition. That this difference is identified here in the sub-acute and chronic groups is a new finding and strengthens our confidence in using the DS condition and ML RMS sway as an important stance position and metric. Further, that there were no significant differences in ML RMS sway between the sub-acute and chronic mTBI cohorts or age groupings for the DS condition is also an important contribution.

A relatively similar picture was painted for the TS condition and the ML RMS-Av, with both showing group and age effects for ML RMS sway. In both cases, this presented as 1) the chronic group having more sway than the control and the sub-acute mTBI groups, but no differences between the controls and the sub-acute mTBI group, and 2) the older adults having more ML RMS sway than the young and middle-aged adults, but no differences between the young and middle-aged adults. From a clinical perspective, tracking sway in the TS or the ML RMS-Av may be beneficial in tracking those with persistent balance issues after mTBI. Further, there is a need to observe older adults in comparison with age-based norms. The main difference between TS and ML RMS-Av findings lay in the fact that gender was a significant covariate for ML RMS-Av, but not TS. This may be a result of the ML RMS-Av incorporating the SS condition, where gender appeared to be an important factor in the calculation.

Although gender has been found to play a role in differences in postural control of younger age groups performing the full BESS protocol, its significance here, in adults, was less clear. In the study by Linder and colleagues, the difference in balance performance between genders was significant at the youth and high-school, but not college age, which was the youngest age group we report on. In earlier investigations of how age and gender affects postural control, Hageman et al., similarly found no effect of gender, but an effect of age, with older adults (60–75 years) demonstrating more sway (larger sway area and longer path length) than younger adults (20–35 years) across various stance positions tested. Although our age groupings are different, our data show similar findings, with the young (18–29 years) and middle-aged (30–44 years) adults having less sway than the older adults (45–60 years) across SS, TS and the ML RMS-Av. Given these findings, a combination of age and gender norms may not be necessary when assessing the least complex stance condition of DS, but may be an important factor to consider when accessing norms of instrumented mBESS performance in other conditions, or when assessing average performance.

General discussion

Taken together, perhaps the most motivating finding is that of both analyses, the DS condition provided the clearest difference between control and mTBI groups. Within the athlete analysis, the only significant differences between athletes with acute mTBI and athlete controls occurred in this condition. In similar vein, the DS condition differentiated between the control group and both the sub-acute and chronic mTBI groups, and was not different between age groups. Accordingly, we would suggest that measuring instrumented DS may provide an initial guiding point for assessment when a patient presents with symptoms after a potential mTBI, regardless of the time since or mechanism of injury that they present to a clinic.
Across both analyses performed, the remaining findings are perhaps more subtly useful. For example, the SS, TS and ML RMS-Av may not provide any further benefit to testing with an athletic sample. This in itself is a pertinent finding. A study compiling injury data from the NCAA estimated around 10,560 sports related mTBI are reported annually. As a result, there have been continued calls for improving diagnosis and management of mTBI in this population. Reducing the evaluation time by cutting out potentially redundant test conditions may be beneficial to clinicians performing both sideline testing and post-injury management in the clinic. This could practically move testing from the typical subjective observational assessment with the mBESS pre and post injury to a single stance instrumented assessment post injury. Comparatively, in the general population evaluated across age-group and mTBI cohort, knowing that more sway was present for the chronic mTBI group compared with the controls and the sub-acute mTBI population completing the TS and in the ML RMS-Av, suggests that these stance positions may be useful in monitoring recovery. Though speculative, as someone moves further from the time of injury, increased sway in these conditions may be indicative of a prolonged recovery of postural control systems. Though this was beyond our scope, it presents a potentially interesting area for future investigation.

Limitations
First, we acknowledge the limitation that the acute population in this study were all athletes, and were all in the young-adult age group (18–29 years), and suggest that there is a need to further explore how athlete status affects balance in older adults at different stages of mTBI recovery as well as balance in a non-athletic sample of persons in the acute stage of mTBI. Older adults with a history of physical activity, and recent and current participation in physical activity have been shown to have better balance than their non-exercising counterparts – a finding that highlights the importance of collecting data about athletic status in older populations or specifically collecting data from athlete populations of middle-aged and older athletes. Additionally, there is a general paucity of studies describing the effects of mTBI on balance in non-athletic samples in the acute stage of recovery. We therefore advocate for additional data to be collected to expand these normative data.

Second, during the initial data collection there was no information on the number of hours or years of training that the athletes participated in. While we lack this information, the athlete sample (recruited from Division I, II and III NCAA competition) fit within the refined criteria proposed for athlete status as defined by MacMahon and Parrington, and all athletes were actively engaging in sports training multiple times per week with the intention of improving performance for competition up until the time of injury.

Conclusions
There is a progressive movement toward instrumenting balance testing with wearable inertial sensors after mTBI in laboratory settings. Instrumented procedures are known to increase objectivity and sensitivity, but unfortunately, there has been limited clinical translation. Hypothetically, the lack of translation into the clinic stems from organizational hurdles, such as technical expertise required to interpret instrumented output. Normative values, which have been provided in this study, can help to bridge this gap, and enable both researchers and clinicians to objectively measure and interpret balance in populations effected by mTBI.

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