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Research Report – Research Article

Inertial Sensor Technology Can Capture Changes in Dynamic Balance Control during the Y Balance Test

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Keywords

Dynamic balance · Wearable sensors · Mobile technology · Inertial sensor · Y Balance Test

Abstract

Introduction: The Y Balance Test (YBT) is one of the most commonly utilised clinical dynamic balance assessments. Research has demonstrated the utility of the YBT in identifying balance deficits in individuals following lower limb injury. However, quantifying dynamic balance based on reach distances alone fails to provide potentially important information related to the quality of movement control and choice of movement strategy during the reaching action. The addition of an inertial sensor to capture more detailed motion data may allow for the inexpensive, accessible quantification of dynamic balance control during the YBT reach excursions. As such, the aim of this study was to compare baseline and fatigued dynamic balance control, using reach distances and 95EV (95% ellipsoid volume), and evaluate the ability of 95EV to capture alterations in dynamic balance control, which are not detected by YBT reach distances. **Methods:** As part of this descriptive laboratory study, 15 healthy participants completed repeated YBTs at 20, 10, and 0 min prior to and following a modified 60-s Wingate test that was used to introduce a short-term reduction in dynamic balance capability. Dynamic balance was assessed using the standard normalised reach distance method, while dynamic balance control during the reach attempts was simultaneously measured by means of the 95EV derived from an inertial sensor, worn at the level of the 4th lumbar vertebra. **Results:** Intraclass correlation coefficients for the inertial sensor-derived measures ranged from 0.76 to 0.92, demonstrating strong intrasession test-retest reliability. Statistically significant altera-

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tions ($p < 0.05$) in both reach distance and the inertial sensor-derived 95EV measure were observed immediately post-fatigue. However, reach distance deficits returned to baseline levels within 10 min, while 95EV remained significantly increased ($p < 0.05$) beyond 20 min for all 3 reach distances. **Conclusion:** These findings demonstrate the ability of an inertial sensor-derived measure to quantify alterations in dynamic balance control, which are not captured by traditional reach distances alone. This suggests that the addition of an inertial sensor to the YBT may provide clinicians and researchers with an accessible means to capture subtle alterations in motor function in the clinical setting.

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Introduction

The quantification of dynamic balance provides a critical window into the function and integration of the sensorimotor system. Accordingly, the measurement of dynamic balance is of interest in both clinical and research settings. The Star Excursion Balance Test and Y Balance Test (YBT) are the most commonly utilised clinical dynamic balance assessments [1, 2]. They require an individual to transition from a position of bilateral to unilateral stance and maintain controlled balance, while performing a maximal reach excursion with the non-stance limb, in a number of standardised directions [2]. A range of indications for the clinical use of the Star Excursion Balance Test and YBT in athletic and pathologic populations have been described, including injury risk factor screening [3–5], injury identification [6], neuromuscular control training [7, 8], and injury rehabilitation [9]. Additionally, previous research has demonstrated the ability of the assessments to identify differences in dynamic balance between control and pathological groups with conditions such as acute lateral ankle sprain [1], chronic ankle instability [10], and anterior cruciate ligament injuries [11].

Dynamic balance requires the maintenance of equilibrium during tasks that involve the movement of the centre of mass outside of the base of support. While the analogue reach distances obtained from the YBT assess how far individuals can reach outside of their base of support, they fail to provide detailed information related to the quality of individuals' balance and the strategy they use to complete the task. Thus, clinicians often rely on subjective visual observations of the individuals' "steadiness" while completing the task. As a result, there is potential that these traditional measures of dynamic balance may not capture subtle sensorimotor deficits possessed by individuals with conditions such as acute lateral ankle sprain [1], chronic ankle instability [12], and concussion [13, 14].

The smart technology revolution of the 21st century has seen the development of inertial sensor-based systems, capable of objectively quantifying human movement [15–18]. Such systems have overcome many of the key limitations of traditional biomechanical systems (such as force platforms and marker-based motion capture), allowing for the unobtrusive quantification of traditional clinical assessments, such as the Timed Up and Go Test [19] and the Balance Error Scoring System [14, 20]. These novel digital biomarkers are capable of capturing subtle alterations in motor function that are present in individuals at an increased risk of falls [19] and following concussive head injuries [14].

Alberts et al. [21] developed a metric to quantify the Balance Error Scoring System, using accelerometer and gyroscope data obtained from the lumbo-sacral region. These accelerometer and gyroscope data were used to calculate a 3D measure of balance (95% volume of ellipse [95EV]), a metric containing the centre of points of sway in 3D, with 95% probability, during the balance task. This study established that data captured using a single inertial sensor mounted on the lumbar spine is of sufficient quality to quantify postural stability, when compared to the gold standard motion capture system. Subsequently, Doherty et al.

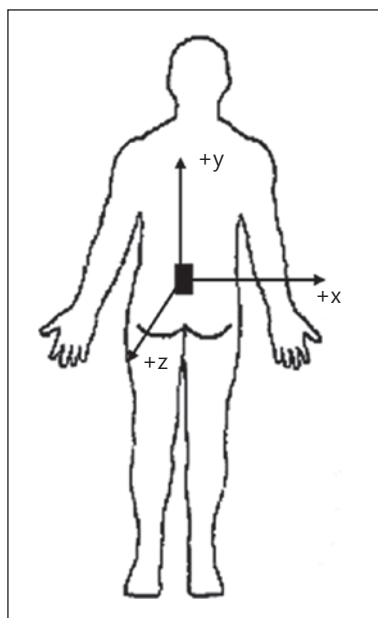


Fig. 1. The shimmer sensor mounting location and axis coordination.

[14] demonstrated the superior ability of the 95EV metric to differentiate concussed and control groups, when compared with the traditional error count.

Recent work has demonstrated the ability of a lumbar-mounted inertial sensor, coupled with machine learning algorithms, to classify fatigue state (fatigued balance vs. non-fatigued balance) during the YBT with moderate levels of accuracy [22]. While this early research demonstrated the potential utility of these systems, such binary classification techniques are not easily visualised and interpreted, limiting their potential impact on clinical practice. Additionally, the ability of such systems to capture changes in dynamic balance, which are not represented by the analogue YBT reach distances alone, has yet to be investigated. As such, sensitive, intuitive and easy to visualise metrics, such as the 95EV, have the potential to provide useful information that can be easily interpreted and thus, leveraged in clinical practice.

Therefore, the primary aim of this study was to compare baseline and fatigued dynamic balance control, using reach distances and 95EV, and evaluate the ability of 95EV to capture alterations in dynamic balance control, which are not detected by YBT reach distances. It was hypothesised that both the reach distances and the 95EV would be affected by the fatigue intervention; however, 95EV would capture changes in control of dynamic balance which were not reflected in the reach distances.

Methods

Participants

Fifteen young healthy adults (sex: 8 female/7 male, age: 23 ± 4 years, weight: 68 ± 8 kg, height: 175 ± 8 cm) were recruited from the wider university community. Participants were eligible to take part if they were aged between 18 and 40 years, actively took part in competitive sport, and did not meet any exclusion criteria. Participants who self-reported that they had sustained a lower limb injury in the last 6 months, had vestibular, visual or balance impairment, cardiovascular disease, any neurological disease, answered yes to any questions on the PAR-Q or had a history of chronic ankle instability were excluded. Ethical approval was



Fig. 2. An individual completing the PL reach direction of the YBT.

obtained from the University Human Research Ethics Committee, and all participants provided informed consent prior to participating in the study. All subjects' rights were protected, and participants were informed that they had the right to withdraw from the study at any point.

Testing Procedures

Individuals were required to attend a single 90-min testing session conducted in the university biomechanics laboratory. An inertial sensor (Shimmer3, Dublin, Ireland) was mounted at the level of the fourth lumbar vertebra, in line with the top of the iliac crests (Fig. 1) to allow for repeatable placement of the sensor, and to closely match estimates of the body's centre of mass, reported to lie in the region of L3–L5 [23, 24]. The inertial sensor was mounted using a custom-made elastic belt, and secured using double-sided tape, to ensure minimal movement artefact. Individuals completed 4 practice trials on their dominant limb (all right leg dominant), as per previously published guidelines [2].

The YBT requires individuals to reach in 3 defined directions: anterior (ANT), postero-medial (PM), and posterolateral (PL) (Fig. 2). Individuals completed 3 YBT trials in each direction (randomised order) on the dominant leg. To establish the reliability of the 95EV measure, this was repeated at 3 time intervals 10 min apart (0PRE, 10PRE, and 20PRE) prior to a fatigue protocol designed to induce a balance deficit.

Individuals then completed the modified Wingate fatiguing intervention. The Wingate test is traditionally used in the assessment of peak anaerobic power and anaerobic capacity [25]. Previous research has demonstrated the detrimental effect various forms of fatigue interventions such as anaerobic exercise [26], high-intensity intermittent exercise [27], lower limb functional exercises [28], and isolated muscle exercises [29] have on dynamic balance. Thus, the introduction of fatigue provided a means to introduce dynamic balance deficits in a controlled laboratory setting.

A modified version of the protocol employed by Carey and Richardson [30] was leveraged in order to induce maximal anaerobic fatigue and introduce a balance deficit. Individuals were required to pedal maximally for 60 s against a resistance set to $0.075 \text{ g} \times \text{kg}^{-1}$. Prior to commencement of the protocol, individuals completed a low-resistance warm-up for 5 min, incorporating 3×5 -s sprints. Individuals then commenced cycling at a cadence of between 50 and 60 RPM for 30 s. Finally, they were instructed to accelerate maximally, while the study investigators provided verbal encouragement to ensure they maintained a maximal effort throughout, resulting in maximal fatigue. Additionally, changes in the power generated were monitored over the course of the test to ensure individuals maintained a maximal effort throughout the Wingate protocol.

Directly following the fatigue protocol, individuals entered the post-fatigue YBT protocol, completing 3 YBTs in each direction at 0, 10, and 20 min (0POST, 10POST, and 20POST), to capture recovery. The traditional YBT scores were captured by recording the maximal reach distance achieved, while the inertial sensor data were captured for the period the individual was in unilateral stance during the reach excursion. Individuals were required to repeat the attempt if they used the sliding block for support, raised the heel of their stance leg, made any ground contact, propelled the block forward with a kick for extra distance, or removed one or both hands from their hips. Reach distances were normalised in relation to the individual's leg length using the formula:

$$\text{Normalised reach distance} = \frac{\text{reach distance (cm)}}{\text{leg length (cm)}} \times \frac{100}{1} \quad (1)$$

Leg length was obtained, by the same investigator for all participants, by measuring the distance between the anterior-superior iliac spine and the most distal aspect of the medial malleolus on the same side.

Data Processing and Analysis

The inertial sensor was connected via Bluetooth to an Android tablet operating Multi-Shimmer Sync software (Shimmer, Dublin, Ireland), and configured to collect tri-axial accelerometer ($\pm 2 \text{ g}$) and gyroscope ($\pm 500^\circ/\text{s}$) data at a frequency of 102.4 Hz during each YBT excursion. These data acquisition parameters were defined based on pilot testing and previous work investigating the utility of inertial sensors in the evaluation of exercise technique [17]. Data were analysed using MATLAB (2012, Mathworks, Natick, MA, USA).

Accelerometer and gyroscope data were filtered with a fourth-order, zero-phase, low-pass Butterworth filter with a cut-off frequency of 20 Hz, and a high-pass Butterworth filter with a cut-off frequency of 3 Hz. Cut-off frequencies were chosen following a preliminary analysis of the signal spectrum, to isolate dominant frequencies elicited by minute postural adjustments during the reach excursion. 95EV was calculated using the following formula:

$$95EV = 4\pi abc / 3 \quad (2)$$

“a” and “b” are the linear acceleration in the medio-lateral axis (accelerometer x) and antero-posterior axis (accelerometer z) and “c” is the transverse plane rotational acceleration (first derivative of gyroscope y) (Fig. 3) [14, 20]. This measure was used previously to measure postural control during the Balance Error Scoring System and shown to have a high correlation with motion capture-derived sway measures [21].

Statistical Analysis

At each YBT testing point, the average of the 3 trials for each reach direction was calculated for the reach distance and 95EV data to ensure measurement reliability [2]. Intraclass

Table 1. The intraclass correlation coefficient results for the 95EV and reach distance variables

Variable	Reach direction	ICC	Lower bound	Upper bound
95EV	anterior	0.76	0.43	0.92
	posteromedial	0.89	0.72	0.96
	posterolateral	0.92	0.80	0.97
Reach distance	anterior	0.99	0.97	1.00
	posteromedial	0.98	0.95	0.99
	posterolateral	0.98	0.94	0.99

ICC, intraclass correlation coefficient.

correlation coefficients (ICCs) were calculated across the pre-fatigue baseline measurements to determine the intrasession test-retest reliability and consistency of the averaged YBT reach distances and 95EV. ICC scores were interpreted using the guidelines put forward by Cicchetti and Sparrow [31]: >0.40 (poor reliability), 0.40–0.59 (fair reliability), 0.60–0.74 (good reliability), and 0.75–1.00 (excellent reliability). The distribution of the data was assessed visually using histograms and quantitatively using the Kolmogorov-Smirnov test, indicating normality of distribution, thus parametric analyses were used. To investigate the effect of the fatigue intervention on dynamic balance, repeated-measures one-way ANOVAs were conducted using the final pre-fatigue (PRE0) and the 3 post-fatigue measurements (POST0, POST10, and POST20) for both reach distances and 95EV. Exploratory post hoc paired-samples *t* tests were conducted to compare PRE20 with POST0, POST10, and POST20 for both the reach distances and 95EV. As the aim of this study was primarily exploratory, a post hoc correction for multiple testing points was not applied as it would increase the likelihood of type II errors, hiding real changes from being considered significant [32]. The level of significance for this analysis was set a priori to $p < 0.05$. Effect size was calculated for each of the post hoc comparisons using the method proposed by Cohen [33]. Percentage change from the PRE20 measure was calculated for both metrics across all 3 post-fatigue comparison points.

Results

Reliability

Normalised reach distance and 95EV ICCs ranged from 0.98 to 0.99 and from 0.76 to 0.92, respectively, for all 3 reach directions, demonstrating excellent test-retest reliability across the 3 baseline pre-fatigue testing points (Table 1). Due to the high level of stability demonstrated by the ICCs across the pre-fatigue assessments, PRE20 was considered the reference measure, and was used in the comparison of balance states.

Pre-Fatigue versus Post-Fatigue

The average reduction in normalised reach distances at POST0 was $2.56 \pm 4.98\%$ (ANT), $2.60 \pm 2.90\%$ (PM), and $3.59 \pm 4.56\%$ (PL). Participants demonstrated an average increase in 95EV of $69.09 \pm 79.76 \text{ deg} \times \text{m}^2\text{s}^{-6}$ (ANT), $47.14 \pm 79.16 \text{ deg} \times \text{m}^2\text{s}^{-6}$ (PM), and $77.23 \pm 109.73 \text{ deg} \times \text{m}^2\text{s}^{-6}$ (PL). Repeated-measures one-way ANOVAs determined that there was a significant main effect of fatigue ($p < 0.05$) on reach distance and 95EV for all directions. The mean percentage change between testing points and the post hoc exploratory paired *t* test analysis comparing the pre-fatigue and post-fatigue balance is presented in Table 2.

Table 2. The post hoc *t* test, effect size and percentage change comparison between the final pre-fatigue and the 3 post-fatigue measurement points

Reach direction	Variable	Testing point, min	<i>p</i> value	Effect size	Percentage change, %
Anterior	95EV	0	0.00	1.03	52.49
		10	0.05	0.76	69.53
		20	0.01	0.96	95.45
	reach distance	0	0.07	-0.35	4.11
		10	0.95	-0.01	0.10
		20	0.38	-0.06	-0.71
Posteromedial	95EV	0	0.03	0.59	37.45
		10	0.02	0.69	46.07
		20	0.01	0.77	81.83
	reach distance	0	0.00	-0.25	2.51
		10	0.09	-0.15	1.31
		20	0.35	-0.08	0.78
Posterolateral	95EV	0	0.02	0.74	51.68
		10	0.04	0.66	55.96
		20	0.00	0.83	59.05
	reach distance	0	0.01	-0.40	3.40
		10	0.05	-0.20	1.56
		20	0.05	-0.25	2.01

Statistically significant ($p < 0.05$) results are highlighted in bold.

Figures 4 and 5 illustrate the group mean changes in normalised reach distance and 95EV between the PRE20 measure and the 3 post-fatigue measures. Figure 3 illustrates the changes in 95EV across the pre- and post-fatigue testing points for an individual participant.

Discussion

The findings of this exploratory study indicate that 95EV, computed from a single lumbar-mounted inertial sensor, can provide detailed information related to an individual's dynamic balance control, which is not captured using traditional reach distances alone.

The ICC results (Table 1) demonstrate the relative consistency between the 3 pre-fatigue measures (PRE0, PRE10, and PRE20) for both the reach distances and inertial sensor-derived 95EV metric. The inertial sensor-derived 95EV metric demonstrated excellent levels of test-retest reliability, ranging from 0.76 to 0.92 for the 3 reach directions. These results show that both reach distance and 95EV measures show excellent levels of relative consistency.

Due to the low levels of within-subject variability in the baseline data set, the PRE20 measurement was chosen as being representative of pre-fatigue balance, and thus was used in the comparison of the pre- and post-fatigue balance states. Figures 4 and 5 illustrate the significant ($p < 0.05$) reduction in mean reach distance and increase in mean 95EV, indicative of poorer dynamic balance. The effect size for the change in 95EV was large (<0.8) for the ANT and PL reach direction and medium (0.5–0.8) for the PM reach direction, while all 3 reach directions demonstrated a small effect size (>0.5) when considering the change in reach distance. The 95EV percentage change from the PRE20 measure showed a larger change than the reach distances, across the 3 reach directions, immediately post-fatigue (Table 2). When

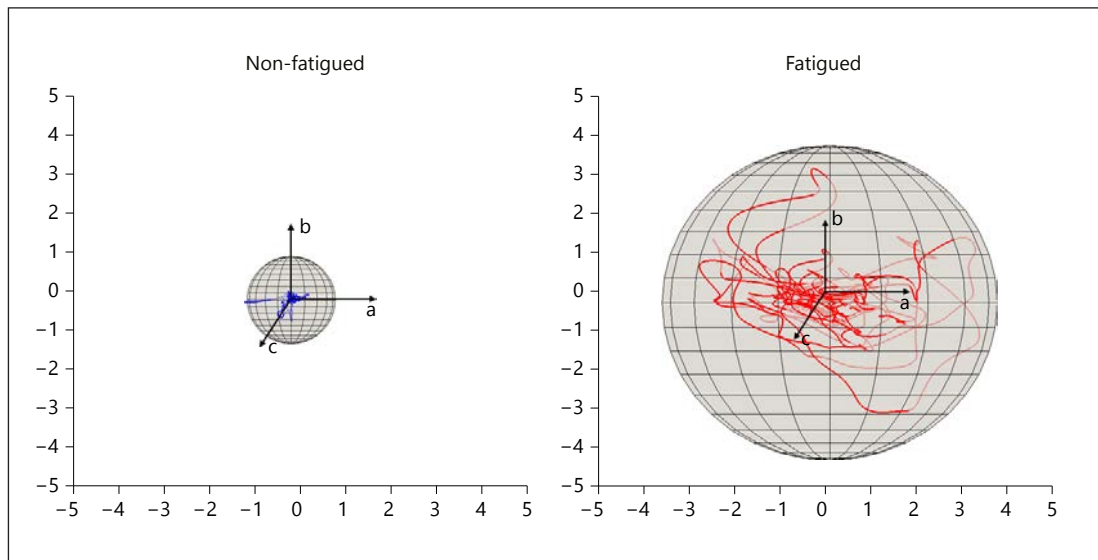


Fig. 3. The 95EV for an individual subject for the ANT reach direction. 95EV was calculated using the formula $4\pi abc / 3$, where “a” and “b” are the linear acceleration in the medio-lateral axis and antero-posterior axis and “c” is transverse plane rotational acceleration.

Fig. 4. The group mean 95EV across the final pre-fatigue and 3 post-fatigue measurement points. Error bars represent the standard error of the mean.

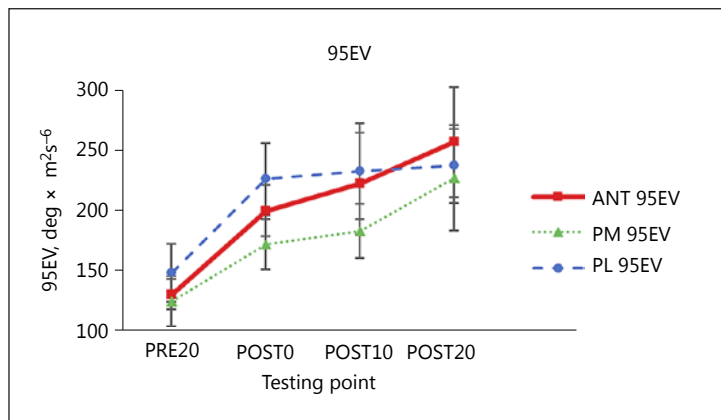
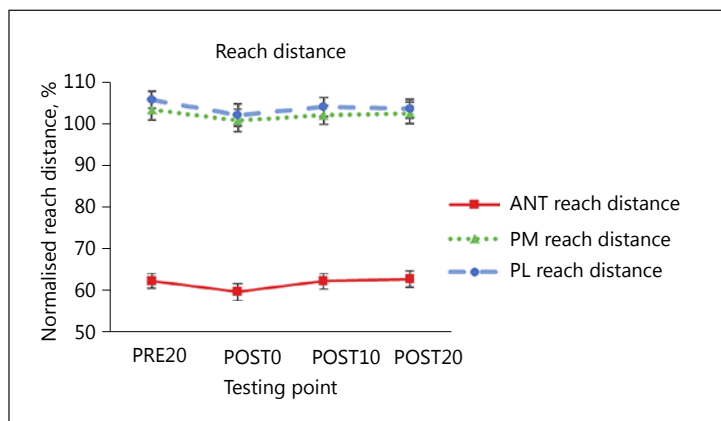


Fig. 5. The group mean normalised reach distance across the PRE20 and 3 post-fatigue measurement points. Error bars represent the standard error of the mean.



the effect size and percentage change are viewed in conjunction, these findings suggest that the 95EV demonstrated a change of greater magnitude than the traditional reach distances. The findings from this study support previously published research demonstrating the negative effects of various fatigue interventions such as anaerobic exercise [26], isolated muscle fatigue [28, 34], lower limb fatiguing exercises [28], treadmill running [35], and high intensity intermittent exercise [27] on dynamic balance.

An important component of this study was to investigate if inertial sensor data could detect alterations in dynamic balance control, despite the return of reach distances to pre-fatigue levels. The results presented in this study demonstrated that there was a statistically significant alteration in dynamic balance as measured by both reach distance (PM and PL) and 95EV (ANT, PM, and PL). However, while reach distances returned to pre-fatigue levels following the initial 10-min period of rest, participants demonstrated a statistically significant increase in 95EV up to and including the 20-min testing point for all 3 reach directions. Additionally, the effect sizes for the reach distances were small (<0.5) for all 3 post-fatigue time points, while the 95EV measure demonstrated a large effect size 20 min following fatigue intervention. The percentage change results illustrate the large and sustained increase in 95EV present for all 3 reach directions: 45.45% (ANT), 81.83% (PM), and 59.05% (PL). In contrast, while there is an initial small percentage reduction in reach distance, this returns to 0.71% (ANT), 0.78% (PM), and 2.01% (PL) by POST20. These findings suggest that a single lumbar-mounted inertial sensor can capture significant alterations in an individual's dynamic balance control, despite the return of reach distances to pre-fatigue levels. Figure 3 illustrates the 3D trace obtained from the lumbar-mounted inertial sensor for an individual subject, at the PRE20 and the POST01 measures. These illustrations are consistent with the 95EV measure, suggesting that they may aid in the visual interpretation of the 95EV metric.

To the best of the authors' knowledge, this study is the first to demonstrate the potential utility of a single lumbar-mounted inertial sensor to provide additional objective information related to an individual's dynamic balance control. Previous work has demonstrated the ability of inertial sensor data to classify fatigued balance performance with moderate accuracy [22]. While the classification method demonstrates that inertial sensor data can capture binary changes in dynamic balance performance, the ability of an inertial sensor system to capture alteration in dynamic balance that are not detected by the analogue reach distances was not investigated. As such, the findings of our study are significant as they demonstrate the potential of a clinically interpretable inertial sensor-derived metric to capture alterations in dynamic balance performance, during the YBT, which are not captured by the traditional method of measurement. Such methods allow clinicians and researchers to track improvements and deteriorations in a person's dynamic balance control.

Limitations/Future Direction

It is worth acknowledging key contextual factors related to this study. Firstly, this research was conducted in a cohort of young healthy adults and did not investigate its application in a clinical population. This allowed us to achieve our primary aim of investigating the ability of an inertial sensor to quantify changes in dynamic balance control, not reflected by the traditional reach distances. Further research is required to investigate the application of this technology in the clinical context. Secondly, no motion capture or force platform system was incorporated into this study. However, 95EV, derived from a lumbar-mounted accelerometer and gyroscope has previously been compared to force platform and 3D motion capture systems [20]. Alberts et al. [20] demonstrated that during components of the balance error scoring system, the kinematic data obtained from an iPad embedded inertial sensor are of sufficient quality relative to motion capture data to accurately quantify static balance. Additionally, the repeated pre-fatigue baseline testing points demonstrated the relatively low

levels of within-subject variability across the 3 time points, indicating its relative stability. This comparison should be interpreted with caution due to different sampling frequency and sensor mounting location utilised in this study. Further research should be conducted to compare inertial sensor-derived measures of the YBT with 3D motion capture systems, to ensure the development of robust and accurate measurements of dynamic balance. It is important to note that due to the challenging nature of the YBT assessment protocol, the test would not be suitable for all clinical populations. Lower functioning populations, such as those with severe physical and cognitive impairments, would not be able to complete the assessment. Such a biomarker may be more suitable for higher-functioning populations, potentially identifying sensorimotor deficits post-injury (musculoskeletal and concussive injuries), aiding in the identification of those who may be at risk of injury in athletic populations and those who may be at risk of falls in older adult and neurological populations. However, further research is required to investigate the application of such a biomarker in these populations.

Conclusion

The findings of this exploratory study demonstrate that the inertial sensor-derived 95EV can differentiate pre-fatigue and post-fatigue dynamic balance control for all 3 reach directions. Additionally, the novel inertial sensor metric can measure alterations in dynamic balance control, despite the return of the reach distances to pre-fatigue levels. These findings suggest that inertial sensor-derived measures of balance may provide an increased level of granularity in characterising the nature of dynamic balance deficits. This may be of value, as the addition of inertial sensors to clinical balance measurements may provide clinicians and researchers with the means to capture micro-level information pertaining to an individual's motor function, in the clinical setting.

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Statement of Ethics

Ethical approval was obtained for the study from the Human Research Ethics Committee of University College Dublin (LS-15-72-Johnston-Caulfield). All participants provided written informed consent.

Disclosure Statement

The authors have no conflicts of interest to declare

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Author Contributions

William Johnston was involved in the study design, data collection, data analysis, and manuscript preparation. Martin O'Reilly was involved in the data analysis and manuscript preparation. Garrett F. Coughlan was involved in the study design, data analysis, and manuscript preparation. Brian Caulfield was involved in the study design, data analysis, and manuscript preparation.

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