Vestibular physical therapy improves turning not straight walking during the inertial sensor-instrumented Timed Up and Go test

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Research

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Abstract

Background: Deficits in vestibular function increase the risk for fall while turning. However, the clinical assessment of turning in patients with vestibular dysfunction is lacking, and evidence is limited that identifies how effective vestibular physical therapy (VPT) is for improving turning performance.

Objective: To quantify and compare walking and turning performance during the instrumented timed up and go (TUG) test using inertial measurement units (IMUs) for clinical settings. We investigate novel instrumented TUG parameters for ability to distinguish patients with unilateral vestibular deafferentation (UVD) from control groups, and discriminate the differences in turning parameters of UVD patients following a VPT program.

Methods: We recruited 38 patients following UVD surgery, 26 age-matched Veteran patient (VA) controls with reports of non-vestibular dizziness, and 12 age-matched healthy controls. Individuals were donned with body-worn IMUs and given verbal instructions to complete the TUG test as fast as safely possible. The IMU-instrumented and automated assessment of the TUG test provided component-based TUG parameters, including the novel walking:turning ratio. Among the UVD patients, 19 patients completed an additional instrumented TUG testing after VPT.

Results: The walking:turning time ratio showed that turning performance in pre VPT UVD patients are significantly more impaired than VA patients and healthy controls ($p < 0.001$). Vestibular rehabilitation significantly improved turning performance and “normalized” their walking:turning time ratio compared to healthy controls ($p < 0.001$).

However, the duration of the straight walking component in UVD patients before VPT was not significantly different as to that after VPT as well as healthy controls.
Conclusions: Our data showed that the IMU-instrumented TUG test can distinguish patients with vestibular deafferentation and objectively quantify the change in their turning performance after surgery. The IMU-based instrumented TUG parameters have potential to quantify the efficacy of VPT and be adopted in the clinic.

Key Words

vestibular hypofunction, rehabilitation, gait, turn, timed up and go (TUG), inertial measurement unit (IMU)

Introduction

Patients with vestibular hypofunction commonly present with dizziness, balance deficits, and gaze disturbance [1]. Such symptoms can cause changes in movement kinematics and compensatory alterations with respect to gait parameters [2]. For example, previous studies have reported significantly reduced head movement during both community ambulation (approximately ten minutes) [3] and during standardized gait testing of short duration [4]. Although such altered movement kinematics may also result in less efficient turning, the current clinical assessment of turning and its related outcome in patients with vestibular dysfunction are not validated. Meta-analysis level data have shown the effectiveness of vestibular physical therapy (VPT) using gaze and gait stability exercises in individuals with vestibular hypofunction [5, 6]. However, the change in turning performance related to the effectiveness of VPT has not been explored.

The Timed Up and Go (TUG) test is a reliable measure of functional gait performance that includes walking and turning 180° as well as transfers to and from a seated position [7]. The ease of administration of the TUG test makes it one of the most commonly utilized measures in VPT [8, 9], and recently, we demonstrated that five weeks of VPT using gaze and gait stability exercises improved the TUG performance despite both pre and post TUG scores being within the clinically accepted normal range [10]. The score from the TUG is simplistic and only considers duration of time and thus lacking an ability to critically evaluate turning performance. To address this limitation, investigators have developed the component-TUG test to individually analyze four unique mobility tasks of the TUG; sit-to-stand and stand-to-sit transitions, straight walking, and turning [11-13].

The component-TUG improves the sensitivity to identify pathokinematics, but it's use is dependent on the expertise of a clinician to identify the abnormal kinematics.

Recently, inertial tracking technologies have begun to be incorporated into physical therapy clinics, which offers quantitative measurement that has the potential to improve clinical outcomes [14-16]. Body worn wireless inertial measurement units (IMUs) have made objective and quantitative measurements of TUG components possible [17-19]. An instrumented clinical assessment tool must be validated uniquely for its intended patient population, given the unique kinematic differences across pathologies. For example, sit-to-stand performance from a chair during the TUG test is significantly associated with fear of falling in the elderly and an important indicator of overall functioning or balance performance [20, 21]. In contrast, the measure of sit-to-stand in patients with Parkinson's disease during the component-TUG test was the least reliable component [18]. Recently, it was reported that several outcomes related to both turning and straight-walking components in patients with Parkinson's disease were significantly impaired relative to healthy controls [17-19]. To date, no comparison of turning and straight-walking components has been considered or reported in patients with vestibular hypofunction.

Individuals who suffer from vestibular hypofunction often have difficulty turning a corner [22]. During the TUG test, increased time to perform a turn and requiring more steps to complete a turn, are associated with difficulty turning [23]. Since one of the primary functions of the vestibular system is to stabilize the body, examining the motion profiles of transitions from straight-path walking to turning while walking may provide clues as to why people with vestibular hypofunction have difficulty during turning, particularly relevant given the head velocities can be high [24]. Additionally, there may exist unique relationships between the total time spent straight walking versus turning. In this study, we quantified the walking and turning components via IMUs and introduce novel IMU-based TUG parameters, including the walking:turning time ratio as well as number of steps ratio. The aims of this study were: 1) to examine the IMU–instrumented TUG parameters during straight walking and turning in patients following unilateral vestibular deafferentation surgery and two control groups; and 2) to determine the differences between the IMU–instrumented TUG parameters following a progressive five-week VPT program in UVD patients. We hypothesized that reduced time and number of steps to perform a turn might improve after VPT.

Methods

Subjects

We enrolled 38 (n = 22 female) patient participants after unilateral vestibular deafferentation (UVD) surgery for resection of a vestibular schwannoma. The patients with UVD were 53 ± 13 years old. We recruited 26 age-matched Veteran patient controls (VA) (n = 0 female) with reports of dizziness not due to vestibular hypofunction based on normal semicircular canal (video head impulse test) and/or otolith function testing (ocular counter roll, vestibular evoked myogenic potential) [25], with a mean age of 56 ± 12 years and an additional 12 age-matched healthy control individuals (n = 7 female) with a mean age of 52 ± 5 years. There was no significant difference in age across the three groups (p = 0.606). With respect to age, no significant differences in sex were found for UVD patients (p = 0.1323) and healthy controls (p = 0.4334). Among the UVD patients, 19 patients (n = 11 female) completed an additional instrumented TUG test after completing VPT, mean duration of 68 ± 45 days later. The study was approved by the Johns Hopkins University and the East Orange VA Healthcare System IRBs. Informed consent was obtained from each individual.

Test procedure and data acquisition

Participants completed questionnaires regarding demographic information. The body worn sensor system that we currently use is comprised of five wireless MTw IMUs, Xsens shirt, and Velcro straps (Xsens Technologies, Netherlands) [26-28]. In this study, acceleration and angular velocities along three perpendicular axes data were analyzed from three IMUs (chest and each ankle) during the TUG test. The IMU sampling frequency was 100 Hz and data were transmitted to the Awinda Station (Xsens Technologies Netherland) before being saved to a tablet PC via USB interface. Specifically, the chest IMU was placed inside the pocket of an Xsens shirt on the right border of the sternum. The ankle IMUs were attached to the ankle just above the lateral malleolus using Velcro straps. Participants were asked to perform three trials of the TUG. The participants were given verbal instructions to stand up from an initially seated position, walk three meters as fast as safely possible, cross a line marked on the floor, turn around a cone, walk back, and sit down. Once testing was completed, participants were assisted with doffing the sensor system.

Data processing and instrumented TUG variables

The TUG test consists of five consecutive tasks; standing up from a chair, straight walking, 180° turning, straight walking, and turning to sitting down on the chair [7]. We analyzed the signal from the ankle IMUs and the chest IMU to segment in two components, i.e., straight walking and turning. The chest IMU gyroscope data for yaw rotation provided a turning direction (e.g. clockwise and counter-clockwise) and an easily distinguished trace for the initiation of turning from a straight-path. Since the time derivative of the turn-angle is the angular velocity, we calculated the trunk angular displacement in the horizontal (yaw) plane by integrating the yaw angular velocity. The mathematical model-based turning segmentation [18] provided the ability to automatically distinguish performance of the individual tasks of the TUG (e.g., straight walking and 180° turning around a cone). We applied the gait event detection algorithm to the pitch angular velocity waveform recorded from both ankle IMUs. The mid-swing event was selected to monitor step counts [29]. Figure 1 shows the segmented phases of straight walking (yellow) and turning (green) and the detected gait event (red circle: mid-swing). The end of trunk rotation was marked with a couple of steps after the second straight walking component (the second yellow shaded area) and denoted the end of the second turn component that occurs as participants return to seated position on the chair. Both the first standing up from a chair and the second turning (returning to sit on the chair) components were excluded from this below analysis.

[Figure 1 here]

This technique was used to determine the TUG variables, which included total time (sec), total number of steps, straight walking time (sec), number of steps straight walking, turning time (sec), and number of steps turn-walking. It is often observed in the clinical setting that a person can ambulate fairly well during the straight-path component, only to slow or modify their gait way while performing the turn. Although the clinician instructs the individual to walk as fast as safely possible during the TUG test, individuals walk with different speeds ranging from slow to fast. Therefore, we also determined the ratio of time period and the number of steps a participant required for individuals to walk straight compared to the time period and the number of steps needed to perform the 180° turn. The walking:turning ratios provides a method of normalizing across the unique and varied patterns of quality of turning motion.

Statistical Analysis

Statistical analysis was performed using SPSS (version 26, Chicago, IL, USA) software. All variables were normally distributed hence, parametric analysis was performed. A one-way ANOVA was performed to compare variables between groups (UVD patients vs VA patient controls vs healthy controls). Post hoc testing using the least significant difference (LSD) correction was applied to compare between groups differences. To evaluate the effect of VPT on the TUG parameters a paired t-test was performed to compare the UVD patients' pre-test results vs. the post-test results. A second analysis between the UVD patients' post-test results and the healthy controls was conducted by independent t-test. The level of statistical significance was set at $p \leq 0.05$. Mean and one standard deviation (1 SD) values of the dependent variables were calculated for each of the test components (straight walking time and steps numbers; turning time and steps numbers; and total time and steps numbers). Descriptive statistics (mean and 1 SD) were used to summarize the results.

Results

Between Groups

Table 1 presents the comparison result of the TUG variables between groups. We found no difference in any of the kinematic variables for turns towards or away from the lesioned ear in the patients with UVD.

[Table 1 here]

<u>Time period variables</u>: The VA controls with dizziness walked significantly slower during the straight component of the TUG compared to UVD patients (25% slower, $p < 0.001$) and healthy controls (32% slower, $p < 0.001$). During the turning component of the TUG, healthy controls were significantly faster than both the VA controls (35% faster, $p < 0.001$) and UVD patients (30% faster, $p < 0.001$). The total time to complete the TUG test were significantly different from each other, with the control group completing it in the shortest duration, followed by the UVD patients (15% slower than healthy controls) then the VA controls (33% slower than healthy controls). In the UVD patients before VPT, the turning time was 61% of the straight walking while the turning time in both healthy and VA controls was 50% of the straight walking time.

Number of steps variables: The VA controls used 15% more steps during the straight component of the TUG compared to the healthy controls (p = 0.004), while the UVD patients trended to also use more steps (9%, p = 0.053) than the healthy controls. During the turning component of the TUG, however, the UVD patients used a 16% greater number of steps, than both the VA patient controls (p < 0.001) and the healthy controls (p = 0.005). The healthy control group used fewer steps during the entire TUG test compared with either UVD patients (12% less steps, p = 0.011) but not the VA controls (10% less steps, p = 0.055).

Walking:turning ratio variables: The VA controls had a significantly higher ratio of walking:turning steps (30% higher, p < 0.001) compared with both the UVD patients and healthy controls (22% higher, p < 0.001). Only the UVD patients had a significantly reduced ratio of time spent in walking:turning (p < 0.001, 19% reduction than both VA and healthy controls).

Effect of Vestibular Rehabilitation

The UVD patients significantly improved after five weeks of VPT in most of the measured TUG parameters. Figure 2 shows an example of the Pre and Post-rehab results in a patient with UVD. The number of steps during the straight walking component before VPT was the same as that after VPT (8 steps). During 180° turning around a cone, the UVD patient 'total number of steps' reduced from five to three, Figure 2. The duration of the straight walking component before and after VPT were 3.92 (s) and 3.65 (s), respectively (p = 0.06). However, after VPT, the turning time was decreased from 2.35 (s) to 1.81 (s), ($p < 0.001$). The walking:turning step ratio after VPT was increased to 2.7 from 1.6 before VPT ($p < 0.001$). After VPT, the walking:turning time ratio was also increased to 2.1 from 1.7 before VPT ($p < 0.001$).

[Figure 2 here]

Table 2 shows walking and turning related variables to identity the effect of VPT.

[Table 2 here]

Time period variables: During the straight walking component of the TUG, the UVD patients walked 9% faster (albeit insignificant improvement, $p = 0.06$) during post-test evaluation of the straight component of the TUG compared to baseline. However, during the turning component of the TUG, the UVD patients were significantly faster post-rehab (27% faster, $p < 0.001$). Additionally, the total time to complete the TUG test was significantly shorter after VPT than pre-rehab (13% faster, $p < 0.001$).

Number of steps variables: During the straight walking component of the TUG, the UVD patients used less steps after VPT, though as above, this was not significant (5% less steps, $p = 0.145$). However, during the turning component of the TUG, the UVD patients used significantly less steps after VPT (36% less steps, $p < 0.001$). The UVD patients also used significantly fewer steps completing the TUG after VPT compared to pre-rehab (15% less steps, $p < 0.001$).

Walking:turning ratio variables: The UVD patients increased significantly the ratio of walking:turning steps compared to pre-rehab (28% increased, $p < 0.001$). Similarly, the UVD patients significantly increased the ratio of time spent in walking:turning (18% increased, $p < 0.001$) post-rehab.

Comparing the UVD patients' post-test results to healthy controls, the data suggests the UVD patients 'normalized' their timing strategies of movement during the TUG test given none of the timing variables were different than the healthy controls ($0.1 < p < 0.361$) (Figure 3). However, the spatial properties of the UVD patients were less altered given, the UVD patients used 10% more steps during the straight component of the TUG compared to healthy controls ($p = 0.007$). During the turning component of the TUG however, the UVD patients used 12% less steps than healthy controls ($p = 0.011$) after VPT. Thus, the UVD patients walking:turning steps ratio was 28% significantly higher than the healthy controls (Figure 3). Finally, after VPT, the UVD patients' ratio of turning time was 50% of their straight walking time, similar with both healthy and VA controls (see the *Between Groups* section).

[Figure 3 here]

Discussion

A clinical assessment tool must be valid, accurate, and reliable within the intended patient group if it is going to be clinically useful. Poor sensitivity of a clinical tool leads to problems with data analysis and interpretation and an unreliable assessment of the efficacy of rehabilitation programs. The TUG is a well-known clinical test of mobility and fall risk with the virtue of being a quick and simple assessment [7-9]. However, recent studies have revealed the limitations of the TUG test and there is conflicting information and opinion about interpreting TUG test results [30-33]. The clinical TUG test measures time, not considering any change in kinematics during various transitions between components. To overcome this limitation, the component-TUG and its instrumented version using IMUs have been suggested and identified as having the ability to classify fallers among the elderly [11, 12], amputee [13], and Parkinson's disease populations [17-19]. However, to the best of our knowledge, only one study has incorporated IMUs to examine the test-retest reliability of the instrumented TUG in patients with vestibular disorders and its association with fall risk [34]. The authors do suggest that the instrumented TUG has potential to enable clinicians and therapists to objectively assess the efficacy of their interventions in patients with vestibular disorders. However, they did not use the instrumented TUG to examine the effectiveness of VPT in patients with vestibular hypofunction; furthermore, no parameters have been derived from IMUs to comparatively analyze the turning sub-component of the TUG in association with straight walking.

Ours is the first study to distinguish patients with vestibular pathology from healthy controls and non-vestibular dizzy patient controls based on the ratio between walking and turning while completing the instrumented TUG. This is a critical result as it has been reported that typical measures of gait, such as the 10-meter walking test, may not provide consistent results in screening patients with vestibular impairments [10, 35-38]. Our data also support this observation given the UVD patients showed no differences in straight walking time before or after completing VPT. However, the UVD patients did demonstrate abnormally increased walking:turning ratios due to significantly slower turning, compared against two control groups. It is also interesting to note that, after VPT, the UVD patients also demonstrated reduced turning time which was half of the straight walking time—similar to the VA and healthy controls. Only the UVD patient group before showed that the turning time was 61% of the straight walking. Our finding suggests the percentage of time spent turning (50%) compared with straight-walking may be a clinically meaningful parameter for distinguishing patients with vestibular hypofunction as well as assessing the effectiveness of VPT in those patients.

Vestibular disorders cause changes in gait behavior [39]; however, the explicit kinematic differences in turning by those with vestibular deficit remains unclear. Furthermore, while there are extensive studies showing how effective VPT is for reducing dizziness and falls in patients with vestibular dysfunction [5,6,10], the contributions of VPT as a treatment for reducing turning difficulties are less understood. In healthy controls, turning 180° around a cone during the TUG involves a smooth and continuous top-down rotation from the head to the trunk [40, 41] with resulting asymmetries in gait parameters between limbs (i.e. stride length and stance time) [42-43]. It is presumed that head movement and upper body coordination during transitions from straight-path walking to turns is critical to ensure a stable position and to aid in gaze stabilization [44-46]. In contrast, deficits in vestibular function cause various disturbances in spatial orientation, gait, head movement, and upper body coordination. It was recently reported that patients with unilateral vestibular hypofunction reveal fewer, smaller, and slower head movements after surgery [3, 4]. Additionally, these authors suggested that early referral for vestibular rehabilitation may be beneficial to improve the recovery of gait, dynamic stability, head movement, and upper body coordination. Our results related to turning performance improvement demonstrated that completing five weeks of the VPT (gaze and gait stability exercises) might restore the normal coordination between the head and upper body.

Limitations

Our data revealed the short-term effects of completing VPT on turning in patients with vestibular deafferentation surgery, it is unknown whether this improvement persists. Patients with other causes for vestibular hypofunction may display different results. Additionally, we did not compare outcomes against multi-segmental coordination from the upper body which may reveal additional compensatory strategies. Future research is needed to fully understand the potential benefits of vestibular rehabilitation on head movement and upper body coordination during turning.

Conclusions

The findings of this study suggest the commonly used clinical version of the TUG test can be instrumented to distinguish patients with surgical vestibular deafferentation and identify improvement of turning ability after vestibular rehabilitation.

List of Abbreviations

IMU: inertial measurement unit, LSD: least significant difference, SD: standard deviation, TUG: timed up and go, UVD: unilateral vestibular deafferentation, VA: Veteran Affair, VPT: vestibular physical therapy.

Ethics approval and consent to participate

The study was approved by the Johns Hopkins University Ethics Committee (Reference Number: IRB00059430) and the VA New Jersey Health Care Systems and the Human Research Protection Office of the Department of Defense (Reference Number: 01386), titled "Sensorimotor Assessment and Treatment of Vestibular Dysfunction." An informed consent was obtained from all the participants of the study.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated during and/or analyzed during the current study are not publicly available due to privacy laws and other restrictions but are available from the corresponding author on reasonable request.

Competing interests

All authors declare that there is no proprietary, financial, professional or other personal interest of any nature or kind in any product, service or company that could be construed as influencing the position presented in this study.

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Authors' contributions

Kyoung Jae Kim: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Writing - review & editing, Visualization. Yoav Gimmon: Validation, Formal analysis, Data collection, Writing - original draft, Writing - review & editing. Jennifer Millar: Data collection, Writing - review & editing. Kelly Brewer: Data collection, Writing - review & editing. Jorge Serrador: Data collection, Writing - review & editing. Michael Schubert: Investigation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. All authors read and approved the manuscript.

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Figure 1. An example of the segmented TUG phases (straight walking and turning) and the detected gait event (mid-swing).

Figure 2. Comparison between pre and post TUG performances. Top: pre VPT, Bottom: post VPT. See Figure 1 legend. Note that both Pre and Post VPT TUG total time scores would be considered as normal.

Figure 3. Comparison of walking:turning ratio parameters (error bar: 95% confidence interval). * Significant difference between groups.

Table 1. Between groups results: mean ± SD (95% confidence interval).

Parameter	**UVD** (N=38)	**VA Controls** (N=26)	**Healthy Controls** (N=12)
Straight Walking Time (s)	3.6 ± 0.87 (3.48 - 3.81)	**4.5 ± 1.16*** (4.24 - 4.76)	**3.4 ± 0.56‡** (3.19 - 3.61)
Turn Walking Time (s)	**2.2 ± 0.53†** (2.15 - 2.36)	2.3 ± 0.49 (2.23 - 2.45)	**1.7 ± 0.31‡** (1.67 - 1.91)
Total TUG Time (s)	**5.9 ± 1.27†** (5.66 - 6.14)	**6.8 ± 1.49*** (6.51 - 7.18)	**5.1 ± 0.82‡** (4.88 - 5.49)
Straight Walking # of Steps	**7.4 ± 1.90†** (7.10 - 7.82)	7.8 ± 1.41 (7.51 - 8.15)	**6.8 ± 1.09‡** (6.39 - 7.21)
Turn Walking # of Steps	**4.3 ± 1.21†** (4.15 - 4.61)	**3.7 ± 0.87*** (3.53 - 3.93)	3.7 ± 0.62 (3.53 - 4.00)
Total TUG # of Steps	**11.8 ± 2.83†** (11.31 - 12.37)	11.5 ± 1.97 (11.12 - 12.01)	**10.5 ± 1.50‡** (10.01 - 11.13)
Walking:Turning Time Ratio	**1.6 ± 0.35†** (1.57 - 1.71)	**1.9 ± 0.43*** (1.84 - 2.04)	1.9 ± 0.26 (1.82 - 2.02)
Walking:Turning Steps Ratio	1.7 ± 0.41 (1.67 - 1.82)	**2.2 ± 0.52*** (2.06 - 2.30)	**1.8 ± 0.31‡** (1.71 - 1.94)

One-way ANOVA comparison is significant for all variables.
***** Significant difference between UVD patients and VA controls.
† Significant difference between UVD patients and healthy controls.
‡ Significant difference between VA controls and healthy controls.
Based on a post hoc tests with LSD correction for between groups comparisons.

Table 2. Effect of VPT pre-post results in 19 UVD patients: mean ± SD (95% confidence interval).

Parameter	UVD Pre-Rehab	UVD Post-Rehab	P value
Straight Walking Time (s)	3.9 ± 0.95 (3.65 - 4.13)	3.6 ± 0.63 (3.50 - 3.82)	P=0.06
Turn Walking Time (s)	2.3 ± 0.51 (2.16 - 2.43)	1.8 ± 0.39 (1.76 - 1.96)	**P<0.001**
Total TUG Time (s)	6.2 ± 1.34 (5.85 - 6.54)	5.5 ± 0.93 (5.28 - 5.74)	**P<0.001**
Straight Walking # of Steps	7.9 ± 2.18 (7.40 - 8.54)	7.5 ± 1.16 (7.28 - 7.86)	P=0.145
Turn Walking # of Steps	4.5 ± 1.46 (4.19 - 4.96)	3.3 ± 0.62 (3.23 - 3.54)	**P<0.001**
Total TUG # of Steps	12.5 ± 3.45 (11.63 - 13.47)	10.9 ± 1.38 (10.61 - 11.32)	**P<0.001**
Walking:Turning Time Ratio	1.7 ± 0.33 (1.63 - 1.81)	2.01 ± 0.34 (1.92 - 2.09)	**P<0.001**
Walking:Turning Steps Ratio	1.8 ± 0.33 (1.70 - 1.88)	2.3 ± 0.52 (2.17 - 2.44)	**P<0.001**

Figures

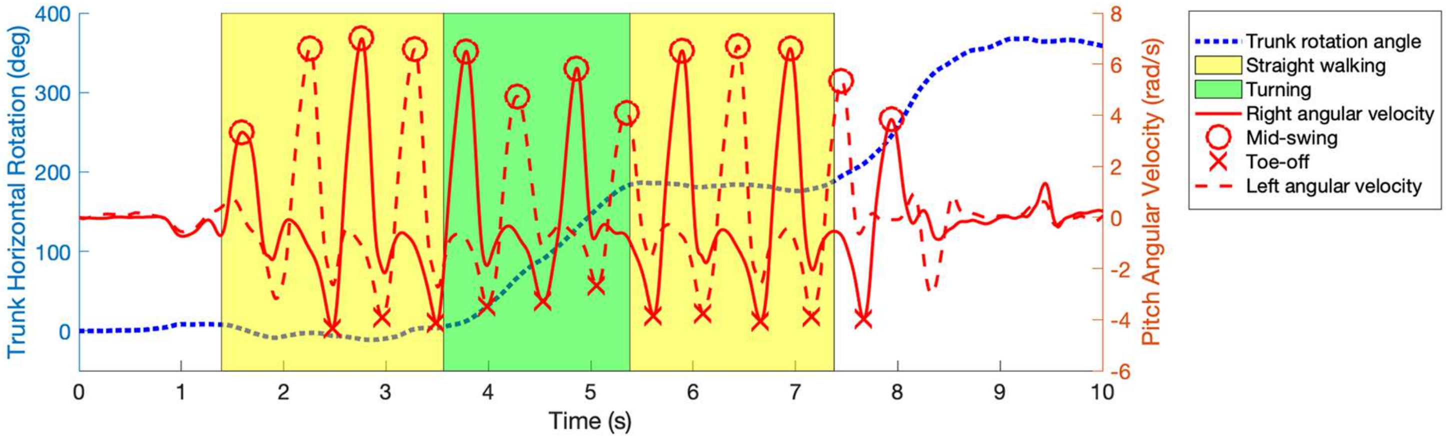

Figure 1

An example of the segmented TUG phases (straight walking and turning) and the detected gait event (mid-swing).

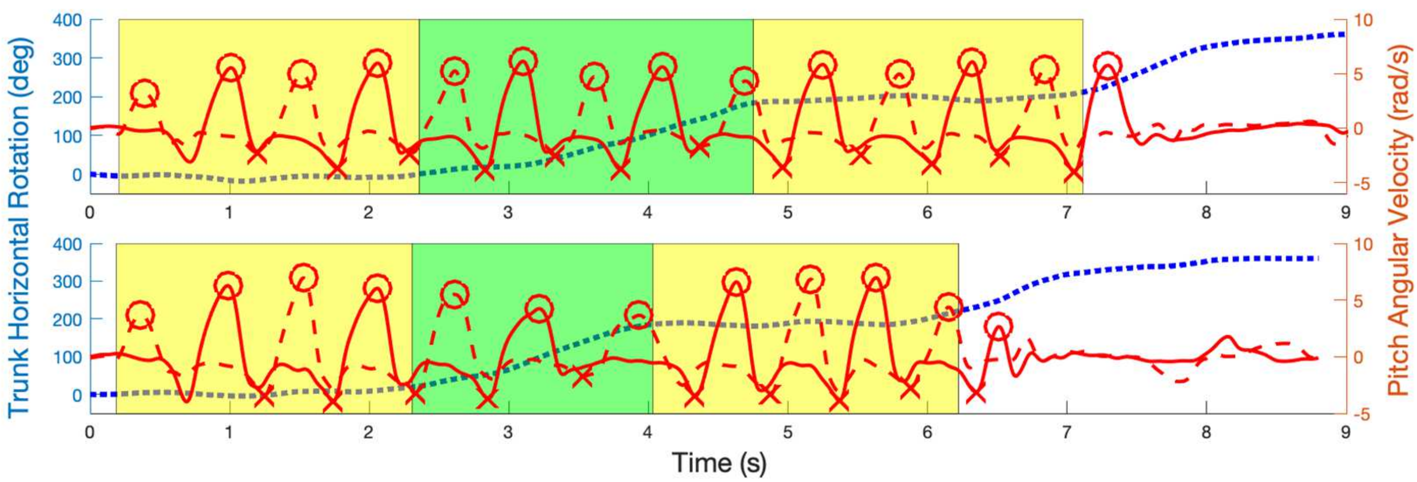

Figure 2

Comparison between pre and post TUG performances. Top: pre VPT, Bottom: post VPT. See Figure 1 legend. Note that both Pre and Post VPT TUG total time scores would be considered as normal.

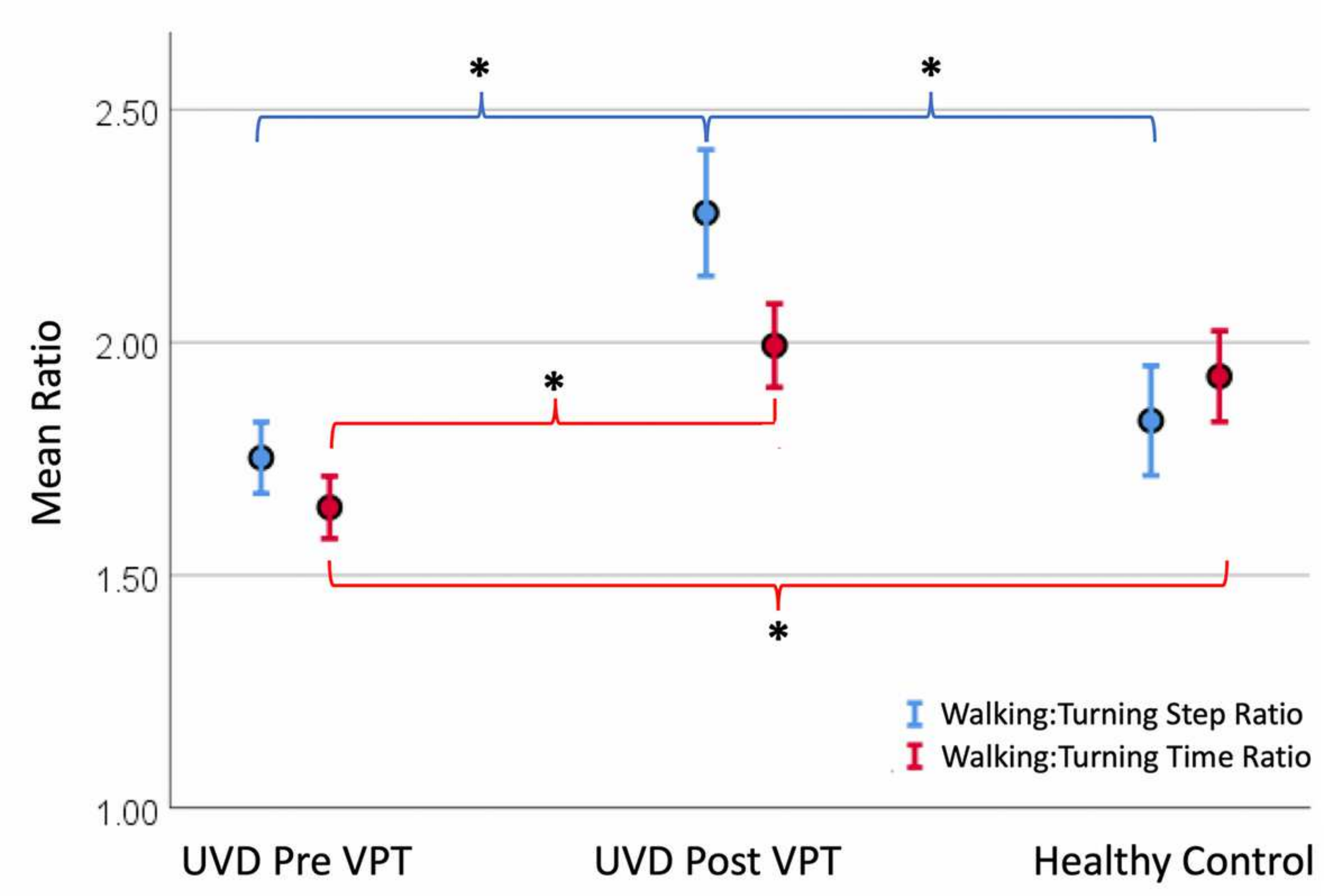

Figure 3

Comparison of walking:turning ratio parameters (error bar: 95% confidence interval). * Significant difference between groups.