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Are Accelerometer-based Functional Outcome Assessments Feasible and Valid After Treatment for Lower Extremity Sarcomas?

Running title: Balance and Gait Assessment in Sarcoma

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This work was performed at the major clinic sites and Human Movement Room at the North of England Bone and Soft Tissue Tumor Service, Newcastle Upon Tyne Hospitals NHS Foundation Trust, UK.

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Abstract

Background Aspects of physical functioning, including balance and gait, are affected after surgery for lower limb musculoskeletal tumors. These are not routinely measured but likely are related to how well patients function after resection or amputation for a bone or soft tissue sarcoma. Small, inexpensive portable accelerometers are available that might be clinically useful to assess balance and gait in these patients, but they have not been well studied.

Questions/purposes In patients treated for lower extremity musculoskeletal tumors, we asked: (1) Are accelerometer-based body-worn monitor assessments of balance, gait, and timed up and go tests (TUG) feasible and acceptable? (2) Do these accelerometer-based body-worn monitor assessments produce clinically useful data (face validity), distinguish between patients and controls (discriminant validity), reflect findings obtained using existing clinical measures (convergent validity) and standard manual techniques in clinic (concurrent validity)?

Methods This was a prospective cross-sectional study. Out of 97 patients approached, 34 adult patients treated for tumors in the femur/thigh (19), pelvis/hip (3), tibia/leg (9), or ankle/foot (3) were included in this study. Twenty-seven had limb-sparing surgery and seven underwent amputation. Patients performed standard activities while wearing a body-worn monitor on the lower back, including standing, walking, and TUG tests. Summary measures of balance (area [ellipsis], magnitude [Root Mean Square (RMS)], jerkiness [jerk], frequency of postural sway below which 95% of power of acceleration power spectrum is observed [f95 of postural sway], gait [temporal outcomes, step length and velocity], and TUG time were derived. Body-worn monitor assessments were evaluated for feasibility by investigating data loss and patient-reported acceptability and comfort. In addition, outcomes in patients were compared with datasets of healthy controls collected in parallel studies using identical methods as in this study to assess discriminant validity. Body-worn monitor assessments

were also investigated for their relationships with routine clinical scales [Musculoskeletal Tumour Society Scoring system (MSTS), Toronto Extremity Salvage Score (TESS), Quality of life-Cancer survivors [QoL-CS)] to assess convergent validity and their agreement with standard manual techniques (video and stopwatch) to assess concurrent validity.

Results Although this was a small patient group, there were initial indications that body-worn monitor assessments were well-tolerated, feasible to perform, acceptable to patients who responded (19 of 20 [95%] found the body-worn monitor acceptable and comfortable and 17 of 20 [85%] found it user-friendly), and produced clinically useful data comparable to the evidence. Balance and gait measures distinguished patients and controls (discriminant validity), for instance balance outcome (ellipsis) in patients (0.0475; 95% confidence interval [CI] 0.0251–0.0810 m^2/s^4) was affected compared with controls (0.0007; 95% CI, 0.0003–0.0502 m^2/s^4; p = 0.001). Similarly gait outcome (step time) was affected in patients (0.483; 95% CI, 0.451–0.512 seconds (s)) compared with controls (0.541; 95% CI, 0.496–0.573 s; p < 0.001). Moreover, body-worn monitor assessments showed significant relationships with existing clinical scales (convergent validity), for instance ellipsis with MSTS (r = -0.393; p = 0.024). Similarly, manual techniques showed excellent agreement with body-worn monitor assessments (concurrent validity), for instance stopwatch time 22.28 +/- 6.93 s with iTUG time 21.18 +/- 6.23 s (ICC agreement = 0.933; p < 0.001). P < 0.05 was considered statistically significant.

Conclusions Although we had a small, heterogeneous study patient population, this pilot study suggests that body-worn monitors might be useful clinically to quantify physical functioning in patients treated for lower extremity tumors. Balance and gait relate to disability and quality of life. These measurements could provide clinicians with useful novel information on balance and gait, which in turn can guide rehabilitation strategies.

Level of Evidence Level III, diagnostic study.

Introduction

Surgical resection or amputation, chemotherapy, and radiotherapy for musculoskeletal tumors in the pelvis and lower extremity have a detrimental impact on the locomotor system [5]. The impaired balance and gait that result [9, 11] often lead to reduced mobility, lack of confidence, loss of adaptive mechanisms to maintain the body in space, and falls [45, 57]. Despite this, balance and gait assessments are not part of routine clinical practice [19]. Balance and gait can be clinically assessed by visual examination or patient-completed scales [20, 52]. However, these methods are subjective, may not detect subtle abnormalities, and some have ceiling effects [25]. Furthermore, difficulties in interpreting results can complicate rehabilitation delivery [25]. Objective functional assessments are therefore potentially useful after sarcoma treatment [19]. Simple tests of balance, gait, or other composite measures, such as the timed up and go (TUG) test, may reflect objective physical capability and fall risk [29, 37, 56].

Despite this, there remains a deficit of valid and reliable objective balance and gait assessments for these patients [19]. A low-cost, accelerometer-based, body-worn monitor has been able to provide valid objective balance and gait data in other patient cohorts [13, 23, 27, 42] and could be of value for monitoring and guiding rehabilitation of sarcoma patients. Different outcome measures are often used to capture outcomes, however, good measures are those that demonstrate accuracy and validity [34, 47, 51]. Body-worn monitors have been sensitive to disability and could detect mild balance differences between patients and controls in diabetic neuropathy [54] and untreated Parkinsonism [37]. Hence, these could be particularly useful in patients treated for a musculoskeletal tumor with mild function abnormalities. Furthermore, it is key to understand whether body-worn monitors are able to satisfy other indicators of validity [34, 47, 51], for example provide clinically useful data,

distinguish sarcoma patients from controls, capture disease-specific outcomes and agree with standard clinic assessments.

Therefore, in patients treated for lower extremity musculoskeletal tumors, we investigated: (1) Are accelerometer-based body-worn monitor assessments of balance, gait, and timed up and go tests (TUG) feasible to use and acceptable? (2) Do these accelerometer-based body-worn monitor assessments produce clinically useful data (face validity), distinguish between patients and controls (discriminant validity), reflect findings obtained using existing clinical measures (convergent validity) and standard manual techniques in clinic (concurrent validity)?

Patients and Methods

The study was approved by the National Research Ethics committee (NREC) (Reference: 13/NE/0296) and the Newcastle upon Tyne Hospitals NHS Foundation Trust, Research and Development department (Reference: 6801). The study was conducted according to Ethical Standards of Helsinki declaration and good clinical practice guidelines.

The Patient Group

We recruited a convenience sample of 34 adult patients (age ≥ 18 years) from the North of England Bone and Soft Tissue Tumor Service, which is located in Newcastle upon Tyne Hospitals NHS Foundation Trust. A convenience sampling of patients was performed to enroll patients who were treated for lower extremity sarcomas. We used this type of sampling in this study to establish proof of concept of the use of body-worn assessments in this clinical group. We included patients if they had undergone treatment, including limb-sparing surgery or amputation and/or radiotherapy, for a lower extremity bone or soft tissue tumor at the iliac crest or below. We excluded patients if they were undergoing active treatment, had benign bone or soft tissue tumors, were unable to take part because of cognitive or physical incapacity, or refused to participate (Fig. 1). All patients provided written informed consent.

We collected demographics and clinical characteristics, including diagnosis, treatments, and time since surgery.

Assessments Using Existing Clinic Measures

Patients completed established measures of disability (Toronto Extremity Salvage Score [TESS]) [8], impairment (Musculoskeletal Tumor Rating System [MSTS] [14, 15]), and quality of life (Quality of life-Cancer survivors [QoL-CS] [16]) at their point of assessment (Table 1).

The Healthy Control Group

Healthy controls from other parallel studies (NREC: 12/NE/0319 and NREC: 09-H0906-82/ 08-H0906-147) provided age-matched references for comparison [33, 61]). Healthy control data, collected by research staff using the same body-worn monitor assessments as our study (described in sections below) were used to compare against the patient group. The healthy control data was collected in the following parallel studies: (1) Pilot work exploring the potential use of the XSens and Open Movement Sensor Device for the Assessment of Osteoarthritis (Osteoarthritis study) which included young healthy control data (age, 19-35 years) (for balance and gait outcomes). (2) Incidence of Cognitive Impairment in Cohorts with Longitudinal Evaluation—GAIT (ICICLE-GAIT) study. This study was a collaborative project with ICICLE-PD, an incident cohort study (Incidence of Cognitive Impairment in Cohorts with Longitudinal Evaluation — Parkinson's disease) that was conducted between June 2009 and December 2011 [33, 61]. It included middle-aged and elderly healthy control data (age, 36-90 years) (for balance and gait outcomes).

To ensure unbiased comparisons, healthy controls were randomly selected from the control datasets. The protocols for body-worn monitor assessment and data processing in patients and controls were identical. We compared demographics such as age, gender, and BMI between

patient and control groups to ensure no differences were present between groups ($p > 0.05$). This was performed to eliminate the confounding effect of demographics on outcomes.

Assessment of Activities Using Manual Techniques

Stopwatch

We assessed the amount of time it took patients to complete 7-meter TUG test with a manual technique (stopwatch) [59]; this test was referred to as "Stopwatch TUG time." We started the stopwatch with the patient sitting upright on a chair and tracked the time it took for the patient to complete five components: standing up, walking 7 meters, and turning around, walking back 7 meters, and returning to a seated position in the chair. The subject wore their usual footwear, and they could use their usual walking aids if required but could not be assisted by another person.

Video

Step count from fast walk test was assessed using observational video analysis. This was referred to as "Video step count."

Equipment

Study participants were asked to wear a triaxial accelerometer-based, body-worn monitor (Axivity AX3, Newcastle-upon-Tyne, UK; dimensions 23.0, 32.5 and 7.6 mm; weight: 11.0 g, sampling frequency 100 Hz, range ± 8 g, Fig. 2A), which has been validated for human movement analysis [6]. The sensor was located on the lower back (over the fifth lumbar vertebrae) within the pocket of a lumbar belt (Fig. 2B). This is close to the center of mass, where readings can quantify a range of physical functioning tasks [24]. The patients wore the device in the clinic for approximately 2 hours and for 7 days in their homes. However, the 7-day data is beyond the remit of this study article. No repeated measures were performed.

147 *Body-worn Monitor Protocol and Data Collection*

148 Participants wore the body-worn monitor in the clinic and underwent standard tests to assess
149 balance, gait, and timed up and go (TUG) outcomes (also referred to as body-worn monitor
150 outcomes).

151 *Test 1: Standing (Balance) Test*

152 Participants were asked to stand upright on a level surface wearing their own footwear, feet
153 slightly apart, hands by their side and eyes open [41] for 120 seconds [38].

154 *Test 2: Intermittent Fast Walk (Gait) Test*

155 Participants were asked to complete three intermittent fast walks; they were instructed to
156 walk as fast as possible without running along a 7-meter walkway [17].

157 *Test 3: 7-meter Instrumented Timed Up and Go (iTUG) (Physical Capability) Test*

158 This test involved standing up from a chair, walking 7 meters at a regular pace, turning
159 around, walking back to the chair and sitting down [62]; participants repeated this test three
160 times. Participants completed feedback forms about acceptability, comfort and user-
161 friendliness of monitors at the end of the assessment.

162 *Data Processing Using an Established Algorithm*

163 Raw data downloaded from the body-worn monitor (using the OMGUI 1.0 Configuration and
164 Analysis software; Axivity, OpenMovement) were processed using established algorithms
165 [12, 13, 24] (Fig. 2C) to derive balance (Supplemental Fig. 1; supplemental materials are
166 available with the online version of *CORR*®), gait (Supplemental Fig. 2; supplemental
167 materials are available with the online version of *CORR*®) and iTUG outcomes
168 (Supplemental Figs. 3; supplemental materials are available with the online version of
169 *CORR*®) using MATLAB® (R2012a, Mathworks, Cambridge, UK).

170 *Algorithm 1# Derivation of Balance Outcomes*

171 We used raw acceleration signals in the AP and mediolateral planes to assess standing balance

in these directions [12, 37, 38]. We captured four balance measures in this study; area, magnitude, jerk and f95 (the highest frequency of sway comprising 95% of the power) of postural sway [12] (Table 1). Area refers to the amount of postural sway, including 95 % AP and ML direction of the acceleration trajectories, and is measured using ellipsis (an elliptical area of postural sway). An ellipsis calculates the scatter of center of mass data and represents the extent to which an individual sways during upright standing. Magnitude of postural sway refers to the root mean square (RMS) of the acceleration signal and is positively related to the metabolic energy cost during upright standing [31]. A low magnitude of postural sway and therefore a low metabolic cost is an optimisation criterion used to set postural control [31]. Jerk, on the hand refers to the 'smoothness of sway' and highlights the postural control of an individual to maintain their balance in an upright position. It is calculated as the rate of change of acceleration signals over time, essentially a time derivative of acceleration. The fourth balance outcome, frequency of sway refers to how often an individual sways in space (number of postural oscillations) whilst in upright standing. f95 is defined as the frequency below which 95% of power of acceleration power spectrum is observed (f95%) [37]. Balance outcomes were normalized over time (120 seconds) for comparison with controls.

Algorithm 2# Derivation of Fast Gait (Gait) Outcomes

Initial contact/final contact events identified from the body-worn monitor vertical acceleration were used to extract gait measures: (1) temporal characteristics, which included individual step, stride (combined left and right step), stance and swing time to complete a fast walk (total gait time) [40] (2) spatial characteristics, such as step length, which were estimated using the inverted pendulum model [63] and (3) spatiotemporal characteristic step velocity calculated as step length/step time. The other gait outcome captured using a body-worn monitor adopting existing algorithms [22] was "step count," also referred to as "body-worn monitor step count" [22].

Algorithm 3# Derivation of iTUG Outcome

Time taken to complete the 7-meter iTUG time was the primary outcome, estimated from raw accelerometer signals using established algorithms [4].

Clinical Interpretation of Normal Versus Impaired Body-worn Monitor Outcomes

Using support from previous evidence, we classified patients with a very high postural sway compared with healthy controls as impaired (poor function) [9] and those with lower values or comparable to healthy controls as unimpaired (good function) (Fig. 3A-D). We classified patients with high temporal values of gait, small step length and reduced step velocity as impaired. Low iTUG time indicated better function (unimpaired) while high iTUG time suggested poorer function (impaired) [62].

Study Outcomes

Our primary study outcome was to investigate whether accelerometer-based, body-worn monitor assessments of balance, gait, and timed up and go tests (TUG) were feasible to use and acceptable. The primary study outcome was evaluated by assessing the number of datasets successfully obtained from patients, data loss during data processing, and acceptability collected through feedback forms. Our secondary outcomes were to study whether accelerometer-based, body-worn monitor assessments showed indicators of face validity, discriminant validity, convergent validity and concurrent validity. The secondary outcomes were assessed by comparing body-worn monitor outcomes to reference values in the evidence, between patients and healthy controls to assess discriminant validity, body-worn monitor outcomes to established clinical scales data to assess convergent validity, and body-worn monitor outcomes to standard manual techniques to assess concurrent validity, respectively.

220 **Statistical Analysis**

221 Parametric data were expressed using means and SDs (min–max) and nonparametric data
222 using medians with interquartile ranges (IQR). Body-worn monitor outcomes were compared
223 between patients and controls, and tumor subgroups using independent t or Mann-Whitney U
224 tests (to assess convergent validity). Bonferroni correction was used to address correction for
225 multiple measures for the between group comparisons. For the related gait variables (step
226 time, step length and step velocity) as the three tests were undertaken, the Bonferroni
227 correction was applied and alpha level was set at 0.05/3 = 0.016. Only those tests showing
228 p values less than 0.016 for the three tests were considered as a significant difference.
229 Pearson's and Spearman's rho correlations were used to assess relationships between body-
230 worn monitor outcomes and clinic measures (for convergent validity). Correlations were
231 classified as strong (-1.0 to -0.5 or 0.5–1.0), moderate (-0.5 to -0.3 or 0.3–0.5) or weak (-0.3
232 to -0.1 or 0.1–0.3). Significance was defined at .05 level. ICC agreement and Bland Altman
233 analysis tested agreement between body-worn monitor measures and standard manual
234 techniques (for concurrent validity). ICC agreements were interpreted as: poor (< 0.5),
235 moderate (between 0.5 and 0.75), good (0.75 to 0.9) and excellent (> 0.9) [35, 46].

236 **Results**

237 In all, 34 adults with a mean age 43 ± 20 years participated (Fig. 1). Recruited patients
238 included those who were treated for bone (21) or soft tissue tumors (13) in the femur/thigh
239 (19), pelvis/hip (3), tibia/leg (9), or ankle/foot (3). Twenty-seven had limb-sparing surgery
240 and seven patients underwent amputation and median time from surgery was 79 months
241 (minimum – maximum, 33–108 months). Fifteen of 34 patients received chemotherapy, and
242 13 of 34 received radiotherapy (Table 2). Details of Individual patients are presented in Table
243 3.

Feasibility, Data Loss and Acceptability of a Body-worn Monitor in the Clinic

The body-worn monitor was feasible to use and quick to set up. Data downloading, processing and derivation of outcomes took approximately 10 minutes. However, it took an additional 10 to 20 minutes to tackle problems if they were encountered during data processing. Of 34 adults who attended the laboratory assessment, one who was wheelchair bound, reported a high level of disability and was unable to participate in any of the laboratory tests, as this patient could not stand and perform transfers. We obtained balance and iTUG data from the remaining 33 adult patients. Three adult patients did not participate in the intermittent fast walk test due to fatigue or lack of time, leaving 30 gait patients for analysis. In addition, one patient's step length outcome could not be calculated as the height of the sensor from the floor was not available. There was minimal data loss; of 34 adult assessments, 33 balance, 29 gait and 33 iTUG datasets were available for final analysis. A larger data loss was seen due to patient not completing the test as opposed to the data been lost during analysis process. Of 20 participants who returned feedback forms, 19 of 20 (95%) found the body-worn monitor acceptable and comfortable, and 17 of 20 (85%) found it user-friendly.

Indicators of Face Validity, Discriminant Validity, Convergent Validity, and Concurrent Validity by Accelerometer-based Body-worn Monitor Assessments

Body-worn Monitor Balance, Gait and iTUG Outcomes in Patients Versus Healthy Controls and Tumor Subgroups

Patients demonstrated alterations of balance and gait compared with controls. Patients presented with higher ellipsis, RMS, and jerk than controls ($p < 0.05$), but with the numbers available, we could not show a difference in frequency of sway ($p > 0.05$) (Table 4). For instance, when comparing patients with controls, ellipsis was 0.0475 (95% CI, 0.0251–0.0810) m^2/s^4 versus 0.0007 (95% CI, 0.0003–0.0502) m^2/s^4 ($p = 0.001$), RMS was 0.0020 (95% CI, 0.0016–0.0036) m/s^2 versus 0.0010 (95% CI, 0.0007–0.0042) m/s^2 ($p = 0.009$) and jerk was 0.0910 m^2/s^5 versus 0.0513 m^2/s^5 ($p = 0.004$). A p value is < 0.05 was considered statistically significant. Patients presented with a large spread of in the above knee tumour groups, showed trends towards a higher ellipsis and jerk (Fig. 4 A-B), compared to the below knee tumour groups.

Patients also presented with higher step time, stance time, swing time, shorter step length and lower step velocity than controls ($p < 0.05$) (Table 4). For instance, on comparing patients with controls; step time was 0.483 (0.451–0.512) seconds (s) versus 0.541 (0.496–0.573) s; $p < 0.001$), stance time was 0.630 (0.576–0.672) s versus 0.680 (0.630–0.724) s ($p = 0.001$), swing time was 0.328 (0.311–0.365) s versus 0.383 (0.348–0.424) s; $p < 0.001$), step length was 0.695 +/- 0.106 m versus 0.641 +/- 0.092 m; p=0.044, not significant after Bonferroni correction for multiple measures was applied; step velocity 1.468 +/- 0.242 m/s versus 1.196+/-0.189; $p < 0.001$. There was also a wide spread of patients' gait values; in step time and step velocity variables (Fig. 5 A-B) (With the numbers available, we could not detect a difference between tumor subgroups ($p > 0.05$) (Table 4).

Patients had a mean iTUG time of 19.49 s (16.61–24.28). No differences were seen between groups; those in the BT group showed values for iTUG time (19.82 s [95% CI, 16.93–24.95]) and the STS group (17.97s [95% CI, 15.86–24.03]) [p value = 0.889]. Patients in the limb-sparing surgery group showed values of iTUG time (19.48 s [95% CI, 16.45 - 24.37]) and the amputation group (19.34 s [95% CI, 16.52–23.79]) [p value = 0.203].

Relationships Between Body-worn Monitor Balance, Gait and iTUG Outcomes and Existing Clinical Scales

Median TESS score was 83.6 (IQR, 62.1–93.8; range, 8.3–100.0), mean MSTS score 24.5 (SD 7.9; range, 5.0–35.0), median 3-meter TUG time 10.8 seconds (IQR, 8.5–12.7; range, 7.9–32.3) s and median QoL-CS total score 7.1 (IQR, 6.1–7.8; range, 2.7–9.1).

Strong or moderate negative correlations were observed between MSTS, TESS, QoL-CS and postural sway (Table 5), for instance ellipsis with MSTS ($r = -0.393$; $p = 0.024$), between MSTS and total gait time ($r = -0.424$; $p = 0.022$) and MSTS and step velocity ($r = 0.424$; $p = 0.022$) and between MSTS, TESS, and iTUG time ($p < 0.05$) (Table 5). This indicates that more structural impairment is associated with impaired balance, gait, and reduced physical capability. A p value < 0.05 was considered significant.

Agreement of Body-worn monitor Measures with Manual Techniques

Gait (Total Steps Measured by Body-worn monitor Versus Gold Standard Video): ICC showed excellent agreement between techniques ($p < 0.05$) (Table 6), for instance stopwatch time 22.28 +/- 6.93 s with iTUG time 21.18 +/- 6.23 s (ICC agreement = 0.933; $p < 0.001$). Similarly step counts recorded by body-worn monitors 13 +/- 3 showed an excellent agreement with step count recorded by video 14 +/- 3 (ICC agreement 0.909; $p < 0.001$). Bland-Altman analysis (Fig. 6) indicated that the body-worn monitor under-estimated step counts by 2 to 5 steps in five patients. Bland-Altman analysis (Fig. 6) confirmed that in a small number of patients, poor

agreement was seen, predominantly in elderly patients who used their hands as support during "sit to stand" and "stand to sit."

Discussion

Assessing patients treated for a bone or soft tissue tumors of the lower extremity is difficult and often subjective. Gait labs can provide some useful information, but they are not commonly available and not used routinely even for research investigations of tumor patients. We therefore wanted to test a body-worn device to assess its potential value and relationship to known clinical assessments of patients with lower extremity sarcomas. This is the first study to our knowledge investigating body-worn monitor assessments of balance and gait after sarcoma treatments. We showed that we could measure several parameters of gait and function with this device and that it could discriminate between different patient groups.

Limitations

One major limitation of this study is that as a pilot study with multiple comparisons and a small sample size the possibility of a Type 1 and Type 2 sampling error respectively, cannot be eliminated. Bonferroni corrections could potentially be used as a solution to correct Type 1 sampling errors related to multiple comparisons [2]; however, these can increase the chances of Type 2 errors [44]. Therefore, the sensitivity of measures to characterise outcomes needs to be assessed in a larger study with a higher power. The heterogeneous sample also makes it challenging to draw robust conclusions for distinct clinical subgroups. The use of healthy controls recruited from different studies introduces potential sources of investigator and selection bias, which are difficult to eliminate from the analysis. Body-worn monitor clinic measures do not necessarily reflect behaviour in the real-world environment, and this needs to be captured separately. Another key limitation is that although most responder patients found this device acceptable; our response rate to the survey was low (59%). Further larger studies are therefore needed.

Feasibility, Data Loss and Acceptability of a Body-worn monitor in the Clinic

We showed that body-worn monitors are feasible and straightforward to use, and at least in those who answered our survey, were acceptable and user-friendly for patients. Clinically useful outcomes could be obtained promptly, with minimal data loss. It was feasible to capture postural control measures characterized by four relatively independent characteristics: area, magnitude, frequency and jerk of sway; rhythm and pace domains of gait and iTUG time. The feasibility of obtaining outcomes in a short time scale, minimal data loss, acceptability, comfort in the clinic and user-friendliness of the device supports the clinical usefulness of the device. As body-worn monitors are portable, functional evaluations could also be performed at in the community, which may be helpful for remote patient assessment. The strengths of the algorithms were that minimal data loss was encountered, and they appeared effective across a range of age groups and functional characteristics [43, 60].

Indicators of Face Validity, Discriminant Validity, Convergent Validity, and Concurrent Validity by Accelerometer-based Body-worn Monitor Assessments

Body-worn Monitor Outcomes in Tumor Patients Versus Controls, Evidence and Across Tumor Subgroups

In our study, patients demonstrated altered balance and gait outcomes compared with healthy individuals, which supports published studies [3, 9, 10]. These results contraindicated De Visser et al. [9] in which no differences were detected between patients and controls by the force platform for the standing (balance) test. This could be because our study included patients after amputation; additionally, triaxial accelerometers may be more sensitive than force platforms [39]. The increased step time, swing time, and reduced step velocity in patients compared with controls also agrees with published reports [3, 10]; however, the higher stance phase and shorter step length in our patients compared with controls contrasts with published studies [10, 48]. This could be because our study used a combined value that

included the affected and unaffected limbs. Differences in step length in our study may also reflect the inclusion of patients with limb-sparing surgery and amputation in different anatomical locations, whereas Rompen et al. [48], only included patients with a femoral endoprosthesis.

After resection of major bone and soft tissues for a lower extremity sarcoma, the loss of sensory [58], motor [7], and proprioceptive [18] systems may disrupt physiological systems, delaying the transmission of sensory data to the central nervous system. Therefore, an appropriate timely response to activate postural muscle groups and maintain balance and posture may not be formulated [28-30]. This might impact gait and performance tests (TUG), explaining a higher iTUG time (poor physical capability) in our study patients [19.486s (16.610 – 24.280)] compared with controls in the literature [14.3 ± 0.5 s] [62] although we do not know if this is a true difference since we cannot directly compare. .

With the numbers we had, we could not detect a difference between BT and STS subgroups, however, and more numbers of patients are needed to determine if our findings will support the findings of others that BTs perform worse than STS and amputation patients perform worse than limb-sparing surgery agrees with the evidence [1, 53]. It also makes clinical sense because BT treatment generally needs more extensive surgery, including bone reconstruction; and after amputation, major limb loss and disrupted sensory and proprioceptive input may lead to poorer function [1, 36]. We could not demonstrate differences (for RMS_ML) until categorized into homogenous groups, which highlights the importance of subgrouping in this heterogeneous patient group.

Body-worn Monitor Measures Against Existing Clinical Measures

In our study, higher impairments (measured by MSTS) related to poor balance, gait, and TUG outcomes. Furthermore, poor balance, gait, and TUG outcomes relate to greater disability and reduced QoL (physical and social components). Relationships between balance

and QoL agree with findings in other clinical conditions [50, 55]. Therefore, simple clinic tests can indicate which patients are at risk of higher disability and reduced QoL. When outcomes in our study were mapped to the widely recognised International Classification of Functioning, Disability and Health (ICF) framework [21], relationships were found to be sensible between the body-worn monitor measures and existing clinic measures (an indicator of convergent validity) and this information could be vital in informing rehabilitation.

Agreement of Body-worn Monitor Measures with Manual Standard Techniques in Clinic

Body-worn monitor measures demonstrated good or excellent agreement with standard techniques, but some instances underestimated step counts. For example, in patients with obvious gait deviations while walking, such as heel drag or low gait velocity (< 1.4 m/s), some steps may not be detected. Slower gait speeds are known to cause step underestimation [32, 49]; synchronization (communication of data) between devices at the start of assessment might help.

Although an excellent agreement was observed between devices, stopwatch time was 1.1 s higher than iTUG time, possibly due to errors in manual timing [26]. The body-worn monitor time starts when the L5 monitor moves upwards during “sit to stand,” whereas the stopwatch runs between the command “Go” and “Stop.” Poorest agreement appeared to be for slower patients in whom the stopwatch had started before the body-worn monitor acceleration threshold was reached, therefore showing body-worn monitor was late in capturing the initial and final phases of the activity. Although the initial and final phases are important to capture, a clear advantage of using a body-worn monitor is that a range of additional measures of postural transitions and gait could be derived [62]. A single body-worn monitor can capture multiple attributes of physical functioning quickly, which is advantageous in busy clinics.

Conclusion

This pilot study supports the feasibility, acceptability, and validity indicators for an

accelerometer-based BWM assessment of balance, gait, and iTUG outcomes in patients treated for lower extremity musculoskeletal cancer. Structural impairments are associated with poor balance, gait, and TUG outcomes, which in turn are associated with greater disability and reduced QoL. Body-worn monitor measures demonstrated excellent agreement between measurements, but in some instances, did not agree with standard techniques. In summary, a laboratory assessment using a body-worn monitor can offer an alternative to cumbersome systems for quantifying balance, gait, and iTUG outcomes.

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Legends

Fig. 1 Flowchart of recruitment

Fig. 2 (A) Photograph of a body-worn monitor device, the Axivity AX3, a triaxial accelerometer that captures acceleration in vertical (X axis), mediolateral (Y axis) and AP (Z axis) directions. (B) Body-worn monitor on the low back at fifth lumbar vertebra (L5) level for laboratory testing. (C) Raw acceleration signal obtained from a body-worn monitor during an activity. The orange line is the acceleration signal measured in the AP direction, the yellow line is the acceleration signal measured in the mediolateral direction, and the blue line is the acceleration signal measured in the vertical direction.

Fig. 3 Examples of normal balance outcome versus impaired balance outcomes in patients are shown here. (A) Normal ellipsis outcome in a 19-year-old male treated with above-knee limb-sparing surgery (excision plus proximal femoral reconstruction) for a bone tumor in the thigh demonstrates a low ellipsis = 0.0113 m^2/s^4, or a small area of postural sway. (B) Impaired ellipsis outcome in a 22-year-old male treated with an above-knee amputation for a bone tumor in the thigh demonstrates a high ellipsis = 0.5890 m^2/s^4, or a large area of postural sway. (C) Normal f95 outcome in a 19-year-old female in the above-knee limb-sparing surgery group (resection of adductor compartment of thigh for a soft tissue tumor) demonstrates a low frequency of sway in the mediolateral direction = 1.160 Hz. (D) Impaired outcome in a 22-year-old male treated with an above-knee amputation for a bone tumor in the thigh demonstrates a high frequency of sway in the mediolateral direction, with a f95_ML = 3.140 Hz.

Fig. 4 Jitter plots to show an increased postural sway in tumor patients compared with healthy controls ($p < 0.05$). (A) Higher ellipsis in patients compared with heathy controls. (B) Higher jerk in patients compared with healthy controls.

Fig. 5 Jitter plots demonstrate an altered gait in tumor patients compared with healthy controls ($p < 0.05$). (A) A higher step time is seen in patients compared with heathy controls. (B) A lower step velocity is seen in patients compared with heathy controls.

Fig. 6 Bland-Altman plots for body-worn monitor measures versus standard manual techniques are shown here. (A) This figure shows the video step count versus body-worn monitor step count. (B) The stopwatch TUG time versus the iTUG time is shown here.

Supplemental Fig. 1

This figure demonstrates the derivation of balance outcomes from the standing (balance) test in a tumor patient. (A) Ellipsis derived from an accelerometer signal: On the y–z [(ML)-(AP)] axis plane, the blue lines are the acceleration signal from BWM and red is the elliptical area which includes 95 % acceleration trajectories in the AP and ML directions. The area of sway was assessed using MATLAB® (R2012a) functions. (B) Frequency in mediolateral direction (f95_ML) derived from an accelerometer signal. The power spectrum is represented in red and final result below which 95% of the accelerations are present are represented by the black dotted line. ML = mediolateral.

Supplemental Fig. 2

This image depicts the derivation of gait outcomes from the intermittent fast walk test in a tumour patient. (A) The raw vertical acceleration signal during a fast walk trial is represented by blue lines, which were used for data processing. (B) In this Zoomshot of initial contact (IC) and final contact (FC) events, the pink diamond dots represent the initial contact and the red dots represent the final contact and are used to derive temporal gait measures (step time, stride time, stance time, swing time).

(C) We used the Inverted Pendulum Model to derive step length. The leg movement reflects an inverted pendulum model, where l denotes the leg length, h denotes the vertical

displacement of L5 level, and step length is calculated. Reprinted with permission from SAGE from Zhao Q, Zhang B, Wang J, Feng W, Jia W, Sun M. Improved method of step length estimation based on inverted pendulum model. Int J Distrib Sens Netw. [Published online ahead of print April 10, 2017]. doi: 10.1177/1550147717702914. Link to the article: http://journals.sagepub.com/doi/abs/10.1177/1550147717702914

Supplemental Fig. 3

This figure shows the iTUG time from the iTUG test in a tumour patient and the method of iTUG time calculation of iTUG time. The algorithm uses the vertical acceleration to detect the first crest representing “sit to stand component” and last crest representing “stand to sit” component. Duration taken to complete iTUG test, also termed as iTUG time was calculated as the time between two crests.