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HEALTH SCIENCES

Smartphone-based evaluation of static balance and mobility in type 2 Diabetes

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Abstract: It was compared smartphone-based measurements of static balance control and mobility of elderly population with and without type 2 diabetes mellitus (DM2). The present cross-sectional study investigated 73 participants grouped in a control group (n = 36) and a DM2 group (n = 37). Smartphone's built in inertial sensors were used to record inertial changes of the participants during static balance and mobility (Timed Up and Go test – TUG) tasks. The inertial variations as a function of the time were analyzed and compared between groups. Both groups were matched in age, body mass index, male-female proportion, but DM2 group had significant larger fasting glucose than control group. Additionally, DM2 group had worst static balance control with open and closed eyes than the controls ($p < 0.05$) as well as they also had longer duration to execute the different events of the mobility test than the controls ($p < 0.05$). DM2 patients had decline of motor functions compared to controls and the use of bult-in sensors of smartphones was feasible to identify these functional impairments. The easy access of smartphones could be improving the screening of functional impairments in DM2 patients.

Key words: Diabetes, balance control, mobility, inertial sensors, smartphone.

INTRODUCTION

Diabetes mellitus has experienced a remarkable surge in its global prevalence, affecting around 463 million adults (International Diabetes Federation 2019). The worldwide prevalence of diabetes now stands at 9.3%, with approximately half of afflicted adults (50.1%) remaining undiagnosed, and type 2 diabetes (DM2) constituting over 80% of all diabetes cases (Beagley et al. 2014). Furthermore, prognostic estimates suggest that the number of individuals afflicted with diabetes is projected to increase to 578 million by 2030 and reach 700 million by 2045 (International Diabetes Federation 2019).

DM2 exerts intricate and diverse effects on the peripheral nervous system, resulting in a wide array of clinical manifestations (Muramatsu 2020). Sensory-motor polyneuropathy stands as the most prevalent manifestation of diabetic neuropathy, marked by proprioception loss, diminished tactile sensitivity in the lower extremities (Feldman et al. 2019).

Static balance assessment and the Timed Up and Go test have been recognized as valuable tools for evaluating the relationship between motor function and glycemic status in patients with type 2 diabetes (DM2) (Kazamel & Dick 2015, Azmon et al. 2018). However, there are challenges associated with the application of these tests. The gold standard method for assessing static balance involves the use of force platforms, which can be costly and may not be readily available to patients, especially those in underdeveloped or developing countries and underserved populations (Prosperini & Pozzilli 2013). On the other hand, the Timed Up and Go test, although straightforward, provides only a single performance metric, which is the test duration (Kear et al. 2017).

In recent years, researchers have validated the use of inertial sensors in wearables or smartphones for the assessment of static balance and the administration of the Timed Up and Go test (Picardi et al. 2020, Patterson et al. 2014, Rodrigues et al. 2022). Employing smartphones for static balance assessment yields results more closely aligned with those obtained using force platforms when compared to questionnaires or scales (Bohlke et al. 2023). Furthermore, instrumented Timed Up and Go test, incorporating inertial sensors, facilitate the calculation of various variables related to different events during the test, thereby enhancing the comprehensiveness of the assessment (Ortega-Bastidas et al. 2023). While wearable sensors hold promise for the evaluation of posture and gait, their widespread availability remains limited in many public or private healthcare systems, particularly in low-resource settings. Conversely, smartphones emerge as ideal candidates for motor test instrumentation due to their built-in inertial sensors, widespread accessibility, and familiarity among the global population (Patel et al. 2020).

The primary aim of the current study was to assess static balance and instrumented Timed Up and Go performance using smartphones in individuals diagnosed with DM2 receiving care through the Brazilian public healthcare system. This study involved a comparative analysis between the results obtained from DM2 patients and those of individuals without DM2. Our hypothesis was that the smartphone-based assessments would effectively detect the postural and mobility impairments commonly observed in individuals with DM2.

ABBREVIATIONS

DM2 - Diabetes mellitus 2
M – Male
F – Female
BMI – Body mass index
AP – anteriorposterior axis
ML – mediolateral axis
g – gravity units
s – seconds
rad/s – radians/seconds

MATERIALS AND METHODS

Ethical considerations

The procedures of the present study were approved by the Ethical Committee for Human Research at the Universidade Federal do Amapá (report #5336038). Informed consent, signed by each participant, was obtained before conducting the experiments.

Participants

Seventy-three participants were recruited to partake in the current investigation. Thirty-six participants were categorized as healthy individuals with no prior diagnosis of DM2, while the remaining thirty-seven participants had a confirmed diagnosis of DM2. None of the participants had a clinical history of motor disorders, and they did not report any motor-related complaints during the experimental period. The DM2 patients were receiving healthcare within the Brazilian public healthcare system in the city of Macapá, Amapá state, Amazonian region, Brazil. All DM2 patients had previously received a formal diagnosis and were undergoing pharmacological treatment with hypoglycemic drugs, with no documented occurrences of diabetic polyneuropathy symptoms. On the same day on which motor assessment procedures were to be conducted, all control participants and patients with DM2 had their blood drawn for fasting blood glucose evaluation.

Experimental procedures

We employed a smartphone (Redmi Note 10, Xiaomi, China) for the assessment of static balance and mobility through the Timed Up and Go test. The smartphone was equipped with built-in inertial sensors (lsm6dso system comprising a tri-axial digital accelerometer and gyroscope, with an acceleration range of ± 8 g and an angular rate range of ± 500 dps, STmicro, acquisition rate of 50 Hz) to capture inertial changes during the tasks. Positioned in proximity to the L5 vertebrae on the lower back, the smartphone was securely fastened to the body using an elastic band. To access the smartphone's built-in inertial sensors during task performance, we utilized an Android application (Momentum Science app). This application has been employed by our research group in prior studies (Rodrigues et al. 2022, Moraes et al. 2023, Santos et al. 2022).

For the evaluation of static balance, each participant received instructions to stand upright without shoes, with their arms naturally resting by their sides. Participants were specifically instructed not to make any voluntary movements during the inertial recording. Sixty seconds of data were recorded in this stationary position, and the test was conducted under two conditions: one with open eyes and another with closed eyes. A one-minute interval was provided between each attempt, and the testing conditions were randomized among the participants. One trial in each condition was done.

For the instrumented Timed Up and Go test, participants were instructed to sit in a chair with their hips and knees flexed at a 90-degree angle. Following the experimenter's command, they were required to walk as quickly as possible in a straight line for a distance of 3 meters. Upon reaching the 3-meter mark, participants were instructed to turn around and return to the chair. Once at the front of the chair, they were directed to turn around and sit back down in the chair. Each participant carried out one trial.

Data analysis

The inertial time series data collected during the execution of the experimental tasks were exported as text files for subsequent analysis using Python programming scripts. A 6 Hz low-pass, second order Butterworth filtering was applied to the recordings. In the assessment of static balance, acceleration time series data from both the anteroposterior (AP) and mediolateral (ML) axes were employed. Conversely, for the Timed Up and Go (TUG) test, time series data from all three axes, including acceleration and angular velocity, were utilized.

Figure 1a-g illustrates about both procedures and their analysis for the motor investigation we applied. In the context of static balance evaluation, the accelerometric time series data were detrended, and the following features were extracted from them:

i) RMS amplitude of AP and ML axes: RMS amplitude was calculated using Equation 1.

$$RMS\ amplitude = \sqrt{\tfrac{1}{n}\textstyle\sum_{i=1}^{n} x_i^2} \qquad (1)$$

where x is the AP or ML time series, i is the i_{th} element of the times series of length equal to n elements.

ii) Total deviation: Total deviation was the sum of hypotenuses covered by the acceleration changes in the AP-ML bidimensional space (Equation 2).

$$Total\ deviation = \Sigma\sqrt{x_{AP}^{2} + x_{ML}^{2}} \qquad (2)$$

where x_{AP} and x_{ML} are the time series in AP and ML axes, respectively.

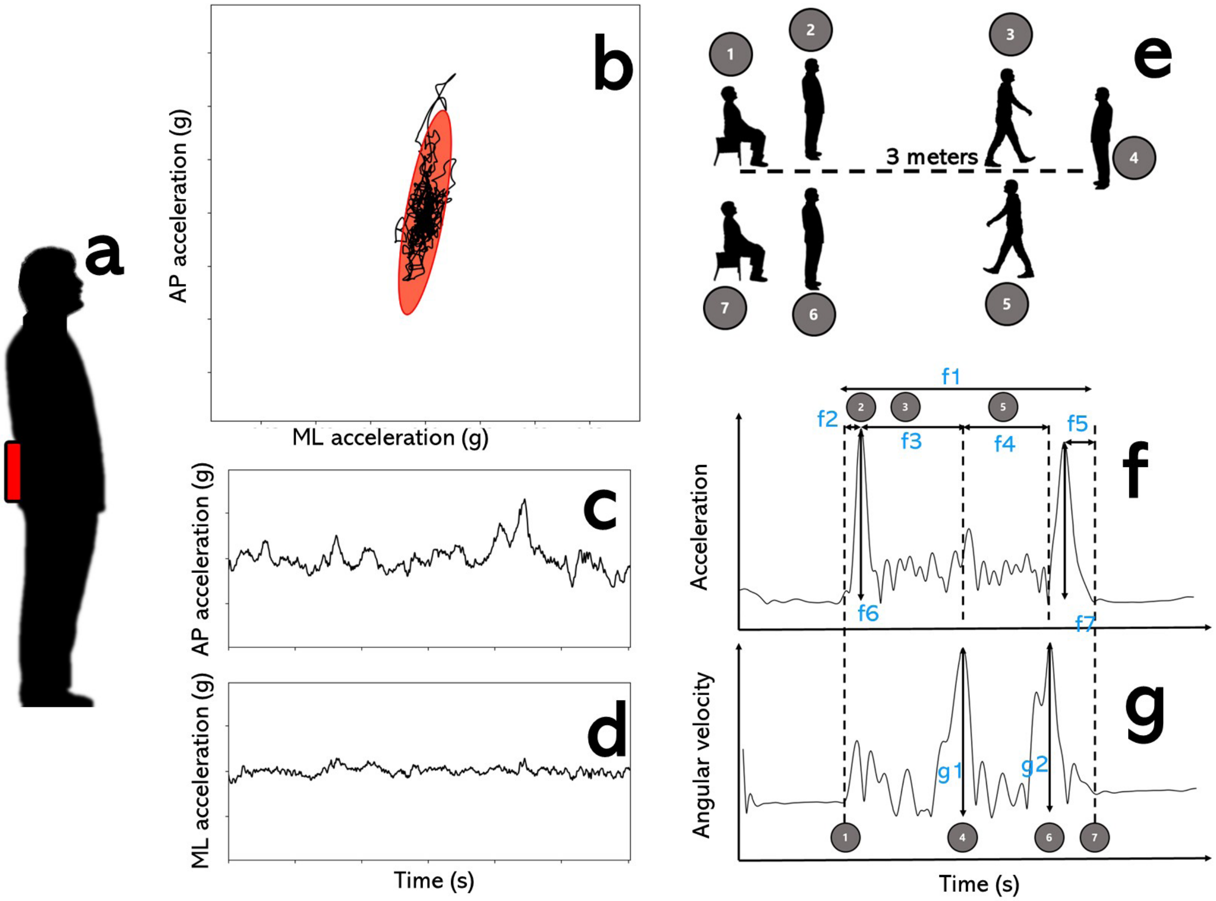

Figure 1. Procedures of testing. For static balance evaluation the recordings occurred with the participant in upright position and smartphone attached to the low back (a). The acceleration changes were analyzed together (b, total acceleration, and ellipse area) or in each axis (c-d, RMS amplitudes). Similarly, the recordings were obtained during the Timed Up and Go test (e). Acceleration recordings (f) e angular velocity recordings enabled to identity inertial transients related to the biomechanical events occurred during the task. The numbers are detailed in the main text.

iii) Area of the ellipses covering 95% of the datapoints in the statokinesiogram: A python code was used to apply an ellipse model that best fitted 95% of the datapoints in the AP-ML bidimensional space.

For TUG test, the time series were detrended and it was calculated the resultant vectors of the acceleration and of the angular velocity following Equation 3.

$$\textit{Resultant vector} = \sqrt{x^2 + y^2 + z^2} \qquad (3)$$

where *x*, *y* and *z* are the time series in AP, ML, and superoinferior axes, respectively. The different stages of test evoked transient components of the inertial recordings as seen in the Figure 1: (1) baseline, (2) sit-to-stand transition, (3) walk go, (4) turn at 3 meters, (5) walk to return, (6) turn in front of the chair, and (7) transition from stand to sit back. ***f1*** is the total duration, ***f2*** is duration of the sit-to-stand transition, ***f3*** is the duration of the 3-meters walk, ***f4*** is the duration to walk back to the chair, ***f5*** is the duration of the stand-to-sit transition, ***f6*** is the maximum acceleration in the sit-to-stand transition, ***f7*** is the maximum acceleration in the stand-to-sit transition, ***g1*** is the maximum angular velocity in the first turn, and ***g2*** is the maximum angular velocity in the second turn.

Statistics

The statistical analysis was performed using the Jamovi software. To assess the normality of the inertial variables, the Shapiro-Wilk test was applied, and differences between the characteristics of each group were assessed using Welch's t-test after data had been adjusted to conform to a normal distribution. Demographic characteristics (age, height, weight, and body mass index), fasting blood glucose levels, and the features extracted from the evaluations of static balance and the Timed Up and Go test were compared between both groups. We computed the achieved power and effect size of the comparisons using G*Power 3.1.9.7 software. A significance level of 5% was considered for all statistical tests.

RESULTS

Clinical and demographic comparison between groups

Both groups were matched in terms of gender, age, and body mass index proportions. As expected, the group of patients with DM2 exhibited higher fasting glucose levels ($p < 0.05$). No participant had clinical findings suggestive of diabetic polyneuropathy in the clinical recordings of the healthcare service. The duration from the DM2 diagnosis was between 3 and 10 years. The mean values related to the clinical-demographic comparisons are shown in Table I.

Table I. Comparison of clinical and demographic features between groups.

	Control group (n = 36)	DM2 group (n = 37)	p-value	Power	Effect Size
Sex (M/F)	8/28	9/28	0.83	0.057	-
Age (years)	63.3 ± 5	63.2 ± 4.6	0.79	0.05	0.02
BMI (kg/m^2)	25.13 ± 3	25.4 ± 3.7	0.73	0.06	0.05
Fasting blood glucose (mg/dl)	95.3 ± 7.5	114.8 ± 10	0.0001*	1.00	2.2

M: male; F: female; BMI: body mass index; *significant difference at level of p≤0.05.

Comparison of the smartphone-based static balance assessment

The comparison of the parameters extracted from the accelerometric time series obtained during static balance task with open eyes shows significant differences for total acceleration, and the area of the ellipses (Table II). For these features, the DM2 group had higher values compared to the control group, indicating worst balance control. No differences were found between the groups in the comparison of the RMS AP and RMS ML parameters in the eyes opened condition ($p > 0.05$). For closed eyes condition, we observed significant differences found in the total acceleration and area of the ellipse, in which DM2 group had larger values than controls ($p < 0.05$). Nonsignificant differences were found for the RMS AP and RMS ML parameters.

Comparison of the instrumented Timed Up and Go test between groups

DM2 group show worst performance than controls in 9 out of 11 parameters of the instrumented Timed Up and Go test (Table III). In general, DM2 group had longer duration of the whole and both stages of the test than the control. Both groups had equivalent durations to stand up from the chair and to change from upright position to the seat position. DM2 groups had less acceleration to stand up and to sit compared to the control, as well as, they also had less angular velocity during the moments to turn than the controls.

DISCUSSION

The present study observed that smartphone was able to identify static balance and mobility impairments commonly observed in DM2 patients, when evaluated using other methods (Dixon et al. 2017). We found that people living with DM2 had loss of balance control in both experimental conditions and had impairment of the mobility during the instrumented Timed Up and Go test.

Some studies have reported postural instability of DM2 patients with and without polyneuropathy (Rosario et al. 2020, Palma et al. 2013, Vaz et al. 2013). Several instruments have been used to assess balance, such as force platforms and pressure sensors, as well as gaming consoles like the Wii, which

Table II. Comparison of the static balance control between groups. The results are represented by the mean (± standard deviation).

	Control group (n = 36)	DM2 group (n = 37)	p-value	Power	Effect Size
Open eyes					
Total deviation (g)	34.3 ± 10.4	49.8 ± 21.7	< 0.001*	0.97	0.91
RMS AP (g)	0.0063 ± 0.002	0.019 ± 0.04	0.08	0.47	0.45
RMS ML (g)	0.004 ± 0.002	0.011 ± 0.03	0.18	0.28	0.33
Area (g^2)	0.007 ± 0.007	0.09 ± 0.2	0.009*	0.7	0.59
Close eyes					
Total deviation (g)	35.8 ± 17.9	51.8 ± 21	0.004*	0.93	0.82
RMS AP (g)	0.011 ± 0.006	0.013 ± 0.006	0.33	0.54	0.49
RMS ML (g)	0.006 ± 0.006	0.007 ± 0.006	0.39	0.1	0.17
Area (g^2)	0.007 ± 0.02	0.028 ± 0.029	0.003*	0.94	0.84

AP: anteroposterior axis; ML: mediolateral axis; *significant difference at level of $p \leq 0.05$.

contains inertial sensors (Lee et al. 2018, Álvarez-Barbosa et al. 2020). The present study aimed to evaluate the use of smartphones as they represent a widely available tool for all populations, are well-received by individuals, and are cost-effective (Álvarez-Barbosa et al. 2020).

Previous studies have reported varying degrees of balance impairment, ranging from generalized static balance deficits (Boucher et al. 1995) to specific conditions such as closed eyes and testing on unstable surfaces (Vaz et al. 2013). Most studies indicate a strong tendency towards increased anteroposterior oscillations with no significant alterations in mediolateral stability (Mengarelli et al. 2023). Our current study found results consistent with previous findings, as we were able to identify alterations only in posturography measures (ellipse area and total deviation). Since we tested patients with long-term glycemic control and no complaints of neurological diseases, these identified losses are only expressed when we combine acceleration information obtained from both axes.

The instrumented Timed Up and Go test has been previously applied to diabetic patients in various investigations; however, its instrumented version has been underutilized (Najafi et al. 2013), and the extent to which various extractable parameters may be related to DM2 remains largely unexplored. Our study found that, similar to other studies, diabetic patients took longer to complete the Timed Up and Go test than the control group. Moreover, it revealed that in addition to this parameter, several other parameters differed between the two studied groups, indicating functional deficits in DM2 patients.

The limitations of this study primarily stem from the characteristics of the studied sample. Both groups had advanced age, which may amplify functional modifications, and all participants belonged to a low-income and low-education demographic.

Our results demonstrate the potential of smartphones in identifying functional deficits in diabetic patients, and due to their ease of access, they can contribute to public health policies in the prevention of complications and the therapeutic monitoring of patients.

Table III. Comparison of the performance in the instrumented Timed Up and Go test between groups. The results are represented by the mean (± standard deviation).

	Control group (n = 36)	**DM2 control (n = 37)**	**p-value**	**Power**	**Effect Size**
Total duration (s)	15.5 ± 1.5	27 ± 4.4	0.001*	1.00	3.49
Time to sit-to-stand (s)	0.97 ± 0.2	0.92 ± 0.2	0.1	0.18	0.25
Time to stand-to-turn (s)	6.06 ± 0.8	11.8 ± 2.1	0.001*	1.00	3.61
Time to turn-to-turn (s)	5.67 ± 1.1	9.9 ± 3.1	0.001*	1.00	2.63
Time to stand-to-sit (s)	1.53 ± 0.3	1.53 ± 0.5	0.98	0.05	0.00
Acceleration peak to stand up (g)	0.75 ± 0.1	0.56 ± 0.07	0.001*	1	2.2
Acceleration peak to sit (g)	0.76 ± 0.1	0.55 ± 0.2	0.001*	0.99	1.32
Maximum speed of first turning (rad/s)	2.59 ± 0.3	1.97 ± 0.4	0.001*	1.00	1.75
Maximum speed of second turning (rad/s)	3.09 ± 0.3	1.63 ± 0.3	0.001*	1.00	4.96
Standing jerk (g/s)	0.74 ± 0.1	0.6 ± 0.1	0.001*	0.99	1.4
Sitting jerk (g/s)	0.52 ± 0.1	0.41 ± 0.1	0.001*	1.00	4.70

***significant difference at level of p≤0.05.**

CONCLUSIONS

Motor impairments associated with DM2 can be identified using inertial sensors from smartphones, what open huge possibilities to expand a low-cost strategy for monitoring of the motor functionalities in DM2 patients.

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TFF, MITCV, GSS designed the project, TFF and FPSP recruited participants, EGRS, GHLP, AB, GSS developed the smartphone application, AACS, ASC, BC, GSS designed the experiments, TFF collected data, TFF and GSS analyzed the data and drafted the firs version of the manuscript. All authors contributed and approved the final version of the manuscript.