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mHealth 6-minute walk test – accuracy for detecting clinically relevant differences in heart failure patients

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Abstract— **Heart failure is a serious disease which increases mortality as well as hospital admission rates for affected patients. Disease management programs supported by telehealth solutions are cost-effective approaches for reducing all-cause mortality and heart failure hospitalizations. A 6-minute walk test (6MWT) app could help heart failure patients to self-monitor their functional capacity. We have developed such an application capable of tracking the geolocation, guiding users through a 6MWT and providing the walked distance after six minutes. Besides common global navigation satellite system (GNSS) filtering methods like a Kalman filter, we have investigated the impact of positioning the device (tablet) and GNSS reception on the accuracy of the test. In a field experiment, we gathered 166 6MWT recordings with the developed mobile application. Applying the Kalman filter reduced the overall relative error from 35.5 % to 3.7 %. Wearing the tablet on the body led to significantly better results than holding it in the hand (p < .001). The average accuracy of 2.2 % of body-worn measurements was below previously defined thresholds for reliable results. It thus allows to define a procedure on how to perform and integrate an accurate 6MWT in telehealth settings for clinical decision support in heart failure patients.**

Clinical Relevance— **Our 6-minute walk test app could help heart failure patients to continuously self-monitor their functional capacity in a telehealth setting.**

I. Introduction

Heart failure (HF) is a chronic disease which is associated with high morbidity, mortality and an increased health expenditure [1,2]. The prevalence of HF is estimated to be more than 10% in people of 70 years and older [3]. With an aging population, the prevalence of HF will rise. Multidisciplinary integrated care is a cost-effective approach which can reduce mortality and heart failure hospitalizations [4]. Examples are comprehensive disease management programs [5]. These programs are reaching from self-care support to intensive care supervision [6]. Disease management programs often include telehealth solutions [7]. Telehealth services are already routine-care in Austria for HF patients after hospital discharge. In 2021, remote patient management for one year with guidance by physicians will become routine care in Germany [8]. Usually, in a remote patient management system, vital parameters like blood pressure, body weight, electrocardiograms, patient-reported data and medical feedbacks are transmitted between patients and healthcare professionals [9-11]. Therefore, patients are typically equipped with smartphones and tablets with specialized applications which are frequently used communication tools for the self-monitoring and remote patient management [12].

The evaluation of HF patients' health states is essential to healthcare providers for an effective and sustainable treatment [13,14]. Usually, HF patients are classified in four classes defined by the New York Health Association which addresses their functional capacity [15]. A viable alternative for objective measurement of HF patients' health state is the 6-minute walk test (6MWT). The 6MWT assesses functional capacity of a patient while walking on a flat, hard surface for 6 minutes supervised by medical professionals [16]. Several authors reported that the walked distance serves as a strong predictor of mortality and hospitalization rate as well as for peak oxygen uptake [17,18]. For a non-supervised 6MWT there are different approaches for mobile apps. Jehn et al. [19] showed that unsupervised, self-performed 6MWT at HF patients' home surroundings are reliable, feasible and safe. Capela et al. [20], Salvi et al. [21] and Wevers et al. [22] published accurate 6MWT algorithms for processing the smartphone's accelerometer-gyroscope data. Nevertheless, these algorithms are based on turn detection in an indoor laboratory setting. Other authors used the global navigation satellite system (GNSS) to measure the distance of the 6MWT with fitness trackers and other commercially available GNSS data loggers [23,24]. Stienen et al. developed a GNSS based mobile application and achieved a relative measurement error of 2.7 % with 6MWT performed outside while walking in a straight line [25]. A review by Bohannon et al. [26] reported that a change from 5 % of the walked distance upwards is clinically important. Our objective was to investigate the effects of filtering and device positioning on the results of the 6MWT app on unspecified routes. This should clarify, whether the measurements are accurate enough to detect

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minimal clinically important differences, as required for clinical decision support in a telehealth setting.

II. METHODS

A. Hardware

For the field experiment, we used SAMSUNG Galaxy Tab A tablets (Version: SM-T595, year: 2018, OS: Android Version 9). These tablets feature receivers for common GNSSs like GPS, Glonass, Galileo and Beidou. For reference measurements, we used a NEDO® Professional Wheel with a wheel sizes of 1 m, a resolution of 0.01 m and an accuracy of ± 0.02%, which corresponds to a maximum error of ± 2 cm over 100 m.

B. Mobile application

To record the 6MWT we developed an Android mobile application with a simple interface. The application's main screen contained a timeline of 6 minutes, the signal strength and a test button. After pressing the test-button, the application initialized the GNSS and enabled the start button as soon as the tablet's geolocation was tracked with enough precision (accuracy constantly < 10m). After pressing the start button, an acoustic signal notified the user to start walking. A time display started to count from 6 minutes down to 0. After 6 minutes, another acoustic signal indicated the end of the 6MWT. The raw GNSS data were stored as GPX-files. This light-weight XML data format is used to save waypoints, tracks, and routes. All coordinates are relative to the World Geodetic System 1984 (WGS84). The elevation was expressed in meters. Latitude and longitude were expressed in decimal degrees [27].

C. Experiment design and participants

Four healthy volunteers from our lab used the developed application to record 6MWTs. They chose between different routes within the city of Graz, Austria. Two tablets were used for each test. The tablets were positioned in a protective cover with a handle. One was on the participants' body with a shoulder bag strap, one in their hands. The other hand was used for moving the measuring wheel to obtain reference distance data for every performed test. In order to exclude device characteristics, the carrying position of the device had to be changed between the test cases. Figure 1 shows the different positioning of the tablets (violet tablet: body-worn, blue tablet: hand-held) and the measurement wheel that was used during a 6MWT.

Figure 1. Positioning of the tablets (left and right) and the used measurement wheel (right).

D. Signal processing

Raw GNSS data were processed using Python and its libraries numpy, gpxpy and pandas. Furthermore, we used a Kalman filter based on the Python library pykalman. Next to defining the Kalman filter, this class was used to learn parameters necessary for the model definition. States could be predicted using the provided smoothing function. The following processing steps were performed for each GPX file:

- The GPX files were parsed and processed, segment by segment.
- Latitude, longitude, elevation and time were extracted for each point.
- Resampling to a rate of 1 sample per second was done.
- Padding was applied for filling missing values in the reindexed series.
- The initial state mean was defined by taking the first available values for longitude, latitude and elevation.
- The transition matrix, observation matrix, observation covariance and initial state covariance were defined based on previous work of authors working with GNSS data [28].
- The transition covariance was estimated by the "estimate maximum" algorithm of the pykalman library. The data for the estimation was taken from a similar dataset of our partner institutions. The iterations were limited to 1000.
- The Kalman smoother of the pykalman library was finally used to correct the GNSS data with the defined Kalman filter.

E. Statistical analysis

Values are provided as mean ± standard deviation. For correlation analysis, the Spearman rank-order correlation coefficient was used as some values were not normally distributed. Correlations with a p-value less than .05 were considered as significant. To compare paired values, we used the Wilcoxon signed-rank test. Outliers in the boxplots were defined as measurements outside 1.5 times the interquartile range above the upper quartile of all values. The relative error (E) for filtered and unfiltered data (D) was calculated as in (1) based on the distance-values of the measurement wheel (DMV).

$$E = \frac{\mathrm{abs(DMV-D)}}{\mathrm{DMV}} \quad (1)$$

III. RESULTS

In total, the test participants used the developed application to produce 166 datasets in different terrains. For all tests two tablets were used simultaneously. This resulted in a total of 83 hand-held and 83 body-worn recordings. Table I shows the unfiltered and filtered distances per 6MWT as derived from mobile devices as well as the reference data measurement wheel for different positions. The results of all measurements are combined at the end. Table II represents the error of filtered and unfiltered data compared to the values from the measurement wheel.

TABLE I. TOTAL DISTANCE VALUES FROM ALL 6-MINUTE WALK TESTS

Position	***Number of tests***	***Unfiltered values [m]***	***Filtered values [m]***	***Measurement wheel [m]***
Hand-held	83	590.5 ± 106.6	456.3 ± 99.5	432.9 ± 88.5
Body-worn	83	555.9 ± 99.0	441.1 ± 89.4	
All	166	573.2 ± 104	448.7 ± 94.6	

TABLE II. MEAN ERROR AT DIFFERENT POSITIONS

Position	***Unfiltered values [%]***	***Filtered values [%]***
Hand-held	39.6	5.2
Body-worn	30.9	2.2
All	35.3	3.7

Figure 2 illustrates outliers and the interquartile range of filtered values in body and hand positions with a sample size of 83:83. The two groups were compared to one another by a Wilcoxon signed-rank test and proofed to be significantly different with a p-value < .001.

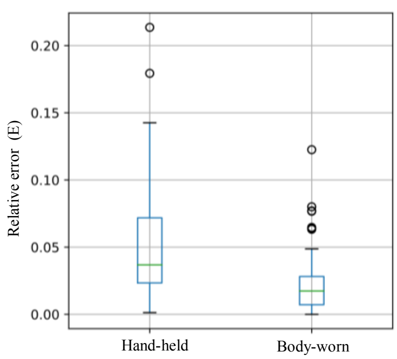

Figure 2. Hand-held vs. body-worn results for filtered values

Table III shows the correlation of the values obtained from the measurement wheel and filtered and unfiltered values from different positions. Figure 3 shows these correlations as scatter plots.

TABLE III. CORRELATION ANALYSIS

Position	***Unfiltered values***		***Filtered values***	
	r	p	r	p
Hand-held	0.62	< .001	0.91	< .001
Body-worn	0.76	< .001	0.95	< .001
All	0.68	< .001	0.93	< .001

IV. DISCUSSION

A high accuracy is essential to detect clinically relevant changes for HF patients or patients suffering from other diseases like COVID-19 associated with limited physical workload in an outpatient setting. The conducted field experiment has shown that not only filtering but also the positioning of the device has a significant impact on the accuracy of the calculated distance of the 6MWT outcomes. Based on the previous publications of other authors, we have chosen a critical value for the maximum tolerable relative error of 5%. Applying the described Kalman filter led to a strong reduction of the error. Nevertheless, many of the errors exceeded the critical threshold. Using only the body-worn recordings reduced the error again by almost half. Except for outliers which can be seen in the boxplot in Figure 2, all measurements have been found to be within the 5 % error range.

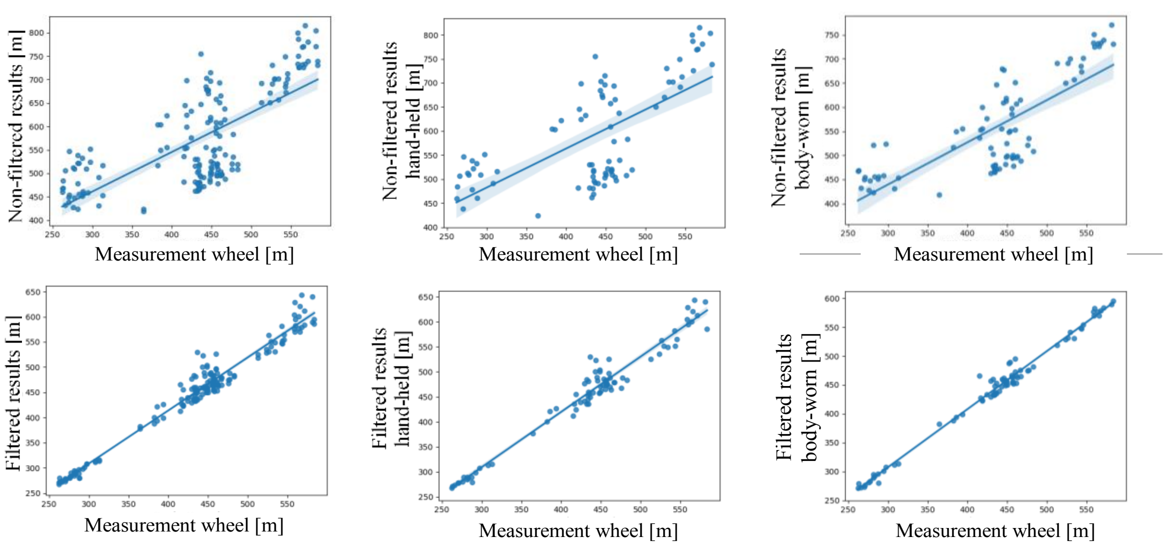

Figure 3. Correlation analysis of filtered and unfiltered 6MWTS.

Tablets were used due to their handiness. It is yet unclear whether the use of smaller devices would lead to similar results. For this application the course has been undefined in contrast to other 6MWT protocols. Consequently, the ability to compare the results with already existing thresholds could be limited and needs to be further investigated. All tests were recorded hand-held and body-worn simultaneously. This led to a one-to-one association between measurements and allowed for a paired comparison. Concerning body-worn 6MWT recordings our results are slightly better than results reported in literature. Our participants walked at different speeds to extensively test our application. This can be seen in Figure 3 as groupings in the data. Nevertheless, we had a lower number of recordings as compared to studies of other authors. A follow-up investigation with patients diagnosed with HF and a higher number of participants is needed, to confirm the results. The next steps are to test the application in the clinical setting before it can be given to HF patients to take home.

V. Conclusion

We used state of the art filtering techniques for GNSS data processing and analysed the impact of device positioning during the 6MWT execution. If the device is properly positioned and strong GNSS signal reception is ensured, clinically relevant changes are detectable. Therefore, the evaluated procedure of the 6MWT can be used in telehealth applications to monitor changes of the patients' functional health status.

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