Reliability and Validity of Garmin Forerunner 735XT for Measuring Running Dynamics In-field

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Abstract

Background: Activity trackers that can measure running dynamics have recently become commercially available. If these devices are to provide real-time feedback on running dynamics and be used in in-field gait re-training or injury prevention, they have to be reliable and valid. However, no in-field evidence of the reliability and validity of these devices exist. **Purpose:** The purpose of this study was to test the reliability and validity of the Garmin Forerunner 735XT paired with the HRM-Run (GFR) running dynamics: Vertical Oscillation (VO), Ground Contact Time (GCT), Step Length (SL), and Cadence during in-field running compared to full body kinematics measured with inertial measurement units. **Methods:** 24 recreationally active subjects ran on a straight path while three-dimensional kinematic data was collected with Xsens MVN Link and running dynamics was collected from the GFR. Two minutes of data were collected across three different running speeds (10, 12, 14 km/h) and two baseline trials. Intraclass Correlation Coefficient (ICC) and Bland-Altman analysis with 95% limits of agreement were used to assess reliability and validity. **Results:** The reliability showed good agreement between baseline trials with ICC(2,k) values ranging from 0.968 to 0.987. For validity the ICC(2,k) revealed a good agreement between GFR and full body kinematic measures for VO, SL, and Cadence ranging from 0.769 to 0.970, while moderate agreement was found for GCT (0.568). Bland-Altman analysis revealed that GFR overestimated VO and underestimated GCT. **Conclusion:** The GFR is a reliable and valid tool for measuring running dynamics in-field. However, GCT and VO must be interpreted with caution.

Keywords: *Activity tracker, running dynamics, reliability, validity, in-field running*

Introduction

The number of runners has gradually increased over the last few decades, and running has now become one of the most popular training activities worldwide (Yamato et al. 2015). The health benefits of running include reducing the risk of cardiovascular disease, type-2 diabetes, osteoporosis and some types of cancer (Warburton et al. 2006). Therefore, running can be prescribed as therapy for several types of metabolic syndrome disorders, heart and pulmonary disease, and muscle, bone, and joint diseases (Pedersen & Saltin 2006). Unfortunately, it is common for runners to experience injuries. A study by Videbaek et al. (2015) found a weighted injury incidence rate of 17.8 in novice runners and 7.7 in recreational runners per 1,000 hours of running. In Denmark, the injury prevalence of active adult runners is estimated to be 21.3 % (Nielsen et al. 2016). Running injuries can occur from a combination of multiple risk factors to a degree where load capacity is exceeded. These risk factors include the number of strides, magnitude of load, distribution of load and load capacity, which is influenced by the runners kinetics, experience and running kinematics (Bertelsen et al. 2017).

A common injury is stress fractures which account for up to 20% of all musculoskeletal injuries in runners (Barnes et al. 2008). Tibia is the most common site for stress fractures which account for about 49% of all stress fracture injuries (Matheson et al. 1987). Rehabilitation from a tibial stress fracture may last 4 - 17 weeks (Willy et al. 2016). In addition, prior fracture composes a sixfold greater risk of recurrence, suggesting a high probability of additional amount of training time lost due to injury (Tenforde et al. 2013).

Studies suggest that abnormal running biomechanics is a risk factor for tibial stress fracture. Both peak hip adduction and high loading rate of vertical ground reaction force have been found in runners with a history of tibial stress fractures. (Pohl et al. 2008, Zadpoor & Nikooyan 2011, Milner et al. 2006). Multiple studies found that gait re-training can be used to effectively and successfully change an individual's running mechanics (Crowell & Davis 2011, Noehren et al. 2011, Willy et al. 2016). Thereby, reducing the vertical loading rate (Clansey et al. 2014, Cheung & Davis 2011) and peak hip adduction (Noehren et al. 2011, Willy et al. 2012).

Gait re-training often involves treadmill running while providing real-time feedback on the lower extremity measured with expensive three-dimensional motion capture equipment, tibial accelerometers or large mirrors (Willy et al. 2012). Furthermore, gait re-training in a laboratory changes the surroundings and routines of running. Even though gait re-training changes can be retained in a one-month follow-up (Noehren et al. 2011, Shull et al. 2013), it is questionable whether the changes in running mechanics are adopted to in-field running when the gait re-training program is concluded. Therefore, specialized equipment for measuring running dynamics in-field is needed.

A substantial growth has been seen in the market of activity trackers, due to becoming more affordable and unobtrusive. Previously, these devices have primarily been used to track steps, distance, energy expenditure, and sleep (Evenson et al. 2015). Recently, activity trackers which can estimate individual's running dynamics using a torso-mounted accelerometer have become commercially available. This includes estimation of Vertical Oscillation (VO), Ground Contact Time (GCT), Step Length (SL), and Cadence (Adams et al. 2016). These biomechanical factors have been shown to impact lower extremity kinetics, and therefore may be used in in-field gait retraining and injury prevention to reduce the risk of lower extremity injury (Wille et al. 2014, Heiderscheit et al. 2011, Hobara et al. 2012, Mercer et al. 2003). Thereby, reducing health care costs by decreasing the number of clinic visits (Willy et al. 2016).

A recent study by Willy et al. (2016) examined the effects of an in-field gait re-training program using real-time feedback from a Garmin wristwatch and a foot pod. The participants successfully increased the preferred step rate and thereby reducing lower extremity impact loading, partly due to a reduction in the vertical center of mass velocity during landing. This indicates that the lower extremity joints are required to absorb less energy (Hamill et al. 1995). Therefore, a change in the preferred step rate may be beneficial in reducing the risk of developing tibial stress fractures (Edwards et al. 2009). This suggests that using in-field gait re-training has the potential to help runners change their running mechanics and potentially reduce the risk of injuries without changing to a laboratory setting or needing unaffordable specialized equipment. Therefore, knowledge about the reliability and validity of these devices is crucial to ensure an unbiased measurement of running mechanics. However, there is limited evidence on the reliability and validity of these devices.

Adams et al. (2016) and Watari et al. (2016) validated similar devices in a laboratory setting. Watari et al. (2016) examined a torso-mounted accelerometer's (Garmin Forerunner 620) ability to measure GCT and VO and compared it to kinetic data from a force plate and the kinematic position of a single retro-reflective marker placed directly on the accelerometer. The study concluded that the device produces a valid measure of GCT and VO, and that the method is a viable alternative to specialized equipment for measuring certain biomechanical variables. Adams et al. (2016) aimed to validate the Garmin Fenix 2 paired with a heart rate strap (HRM-Run; Garmin Ltd) to measure the ability of the watch to detect changes in running dynamics. The study compared data on running dynamics obtained from the Garmin Fenix 2 to motion capture data and kinetic data from a force plate build in the treadmill. The study concluded that the watch was a valid and reliable tool to measure changes in GCT, VO, and Cadence. Furthermore, Adams et al. (2016) suggests that future studies should include the use of similar devices in an in-field environment to give real-time feedback on running dynamics during gait retraining. However, to our knowledge, no study has validated the running dynamics of a commercially available fitness watch in an in-field environment. In addition, the aforementioned studies do not include validation of step length. Therefore, the aim of the current study was to test the reliability and validity of the Garmin Forerunner 735XT by comparing the running dynamics of the watch against full body kinematic recordings based on Inertial Measurement Units (IMU) in-field.

Methods

Subjects

24 subjects (male (n=17), female (n=7), 26.0 $\pm$ 1.3 years, 80,9 $\pm$ 12.0 kg, 179.5 $\pm$ 7.7 cm) were recruited for the study. All subjects were recreationally active for at least 60 minutes per week. Additionally, all subjects had been injury free for at least six months and completed the protocol without any pain or discomfort. Before testing, the subjects were informed about the purpose of the study, experimental design, equipment, and signed a declaration of consent.

Experimental design

The subjects performed five running trials of two minutes on a straight track paved with asphalt at four different speeds. One baseline with self-selected running speed, three running trials with a running speed of 10, 12 and 14 km/h, and a second baseline matching the speed of the first baseline. The order of the 10, 12 and 14 km/h running trials were randomized. However, the first and second baseline was the first and last trial for all subjects. The speed was controlled by a Garmin Fenix 2 GPS watch (Garmin Ltd., Olathe, Kansas, USA) mounted on a bike. 3D kinematic data of the full body was recorded at 240 Hz with a Xsens MVN link motion capture suit (Xsens Technologies B.V, Enschede, The Netherlands). Xsens was considered as the golden standard for the current study. Running dynamic data was recorded with the Garmin Forerunner 735XT (GFR) paired with a heart rate strap (HRM-Run; Garmin Ltd). The measured variables were: Vertical Oscillation (VO), Ground contact time (GCT), Step length (SL), and Cadence.

Procedures

Prior to data collection each subject was introduced to the GFR to become familiar with the start, stop and save function. Anthropometric data for each subject was collected based on instructions provided by the manufacturer (Xsens 2017). The anthropometric data was loaded into the Xsens MVN Studio 4.3 (Xsens Technologies B.V, Enschede, The Netherlands) before calibration. The subjects did a 10-20 minutes warm-up while wearing the heart rate strap and the Xsens MVN Link to get familiarized with running in the suit. An N-pose calibration was performed to do a sensor to segment alignment. If the calibration was categorized as "good" according to the system, it was applied otherwise a new calibration was made. A visual inspection using the live view of the joint movement was performed to make sure the model was consistent with the movement of the subject. The calibration was performed outside to reduce the amount of magnetic disturbance.

Furthermore, the subject wasn't equipped with the GFR until after the calibration was done. Lastly, the subject was introduced to the experimental protocol of the study. For the first baseline trial, the subject was instructed to run with a comfortable self-selected running speed. For this trial, the subject's running speed was recorded. For the remaining three trials and second baseline trial, the speed was controlled by the test leader riding a bike in front of the subject. Another test leader rode behind the subject on a Long John bicycle with a computer, a battery and access point for data collection. The Xsens system was activated first, after which the subject was instructed to perform a jump and start the GFR upon landing to synchronize the two datasets.

Data processing

Data from GFR was downloaded using Garmin Connect software 3.18.1.0 (Garmin Ltd., Olathe, Kansas, USA), and imported into MATLAB R2017a (Mathworks, Inc; Natick, Massachusetts, USA). Data collected in MVN Studio was exported into MATLAB, and filtered using a 2^{nd} order, zero phase, lowpass Butterworth filter with a 10 Hz cutoff. The data was aligned using the jump as an indicator of the start of the Garmin data. Furthermore, 35 seconds of data were disregarded from the start of both systems to make sure the subject had reached a constant speed. Consequently, one minute of data for both systems was used for each trial.

Running dynamics variables were calculated from the Xsens MVN Link data as follows: VO was calculated as the lowest vertical position of the Center of Mass (COM) subtracted from the highest vertical position of the COM for each step. COM was preferred to calculate VO rather than the position of the sternum sensor since body segmental analysis technique provides a better estimate of VO than the position of a single marker (Gard et al. 2004). Heel strike and toe-off were identified using two local maxima of the knee extension angle (Dingwell et al. 2001) (Figure 1). GCT was calculated as the time between heel strike and toe-off. Cadence was calculated as the number of heel strikes and reported as steps per minute. SL was calculated as the distance between two consecutive heel strikes, using the position of the feet.

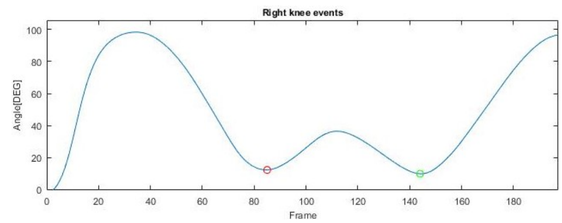

Figure 1: Gait events for the angle of the right knee where the red circle (left) was identified as heel-strike, and the blue circle (right) was identified as toe-off.

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Statistics

The test re-test reliability was assessed using the Garmin data from the two baseline trials. A value of both the relative reliability and absolute reliability for each of the four running dynamic variables was calculated. Relative reliability was expressed with the Intraclass Correlation Coefficient (ICC). For all subjects the mean value of the four variables was calculated. An ICC(2,k) was performed using the baseline as conditions, which was calculated in the following way (Weir 2005):

$$ICC(2,k) = \frac{MS_S - MS_E}{MS_S + k \cdot \frac{MS_T - MS_E}{n}} \quad (1)$$

where MS_S is the between subjects mean square, MS_E is Error mean square, MS_T is trials mean square, k is the number of trials and, n is the number of paired observations (Weir 2005).

The absolute reliability was assessed with the Standard Error of Measurement (SEM) and was calculated for each of the variables (Weir 2005):

$$SEM = SD/\sqrt{2} \quad (2)$$

where SD is the standard deviation of the mean difference between scores (De Vet et al. 2011). Bland-Altman plots were conducted to visualize differences between baseline trials and calculate the Limits of

Agreement (LoA).

Validity for each running dynamics variable was assessed by comparing the data from GFR to the Xsens data. The level of validity was expressed with the ICC(2,k) and calculated as equation 1. The Bland-Altman analysis was performed to visualize systematic differences between the two methods and to calculate the LoA. The plot was created by plotting the mean difference against the difference between methods. The 95% LoA was calculated as Bland & Altman (1986):

$$MD \pm 1.96 \cdot SD \tag{3}$$

where MD is the mean difference between conditions and the SD is the standard deviation of the mean differences between conditions.

The ICC(2,k) values obtained for reliability and validity were interpreted as good if ICC > 0.75, moderate if $0.50 \leq$ ICC ≤ 0.75, and as poor if ICC < 0.50. (De Vet et al. 2011, Gouttebarge et al. 2015). All statistical calculations were performed using MATLAB R2017a.

Results

One subject was excluded from the study, as all running dynamic data from GFR over the two minute was zero, even though heart rate, speed, and GPS data were recorded correctly, and therefore this measurement couldn't be used in further analysis. The recorded mean speed for baseline 1 and 2 was 12.17 $\pm$ 1.56 and 12.06 $\pm$ 1.55 km/h, respectively. The mean absolute difference between baseline trials was 0.43 km/h. The recorded mean speed for the three controlled running trials was: 10.34 $\pm$ 0.51, 11.94 $\pm$ 0.44, and 13.50 $\pm$ 0.51 km/h, respectively.

Reliability

Table 1 presents the mean and standard deviations of each variable obtained by the GFR across all subjects from the two baseline trials. In addition, the ICC(2,k) values and SEM for each of the four variables are presented. The level of test re-test reliability of the GFR was good with ICC(2,k) values of 0.983 for VO, 0.987 for GCT, 0.968 for SL and 0.983 for Cadence, the SEM values were low given the mean values from the baseline trials. For example, mean GCT found in the baseline trials were 248-249 ms and its SEM were 3.88 ms, indicating that an increase or decrease of more than 7.78 ms needs to be reached before it can be interpreted as more than a random measurement error. Bland-Altman plot with the 95% LoA for reliability is shown in Figure 2.

Validity

The ICC(2,k) values for validity can be seen in table 1. Using the calculated variables obtained from the Xsens data the ICC(2,k) values for the GFR were: 0.769 for VO, 0.568 for GCT, 0.935 for SL, and 0.970 for Cadence. Bland-Altman plots for the agreement between the two methods is shown in Figure 3. The Bland-Altman analysis revealed a mean overestimation of 10.17 mm for VO and 0.92 spm for Cadence and an underestimation of -33.12 ms for GCT and -0.05 m for SL. The 95% LoA was found to be: -2.42 to 22.77 for VO, -4.08 to 5.95 for Cadence, -68.53 to 2.29 for GCT and -0.14 to 0.04 for SL.

Table 1: Mean differences, standard deviation, limits of agreement (LoA), ICC(2,k), and SEM values for comparisons between baseline trials and mean differences, standard deviation, LoA and ICC(2,k) values for comparison between Garmin Forerunner 735XT and Xsens MVN Link for Vertical Oscillation (VO), Ground Contact Time (GCT), Step Lenth (SL) and Cadence.

	Reliability					**Validity**			
	Baseline 1	Baseline 2	Bland -Altman	ICC	SEM	Garmin	Xsens	Bland -Altman	ICC
Running variable	Mean (SD)	Mean (SD)	Mean (LoA)			Mean (SD)	Mean (SD)	Mean (LoA)	
VO [mm]	94.85 (13.20)	94.19 (13.23)	0.66 (6.73)	0.983	2.45	94.14 (12.85)	83.97 (10.88)	10.17 (12.59)	0.769
GCT [ms]	248.14 (23.81)	249.50 (25.12)	-1.35 (10.75)	0.987	4.03	252.42 (25.29)	285.54 (25.04)	-33.12 (35.40)	0.568
SL [m]	1.19 (0.15)	1.18 (0.14)	0.01 (0.09)	0.968	0.036	1.19 (0.13)	1.24 (0.14)	-0.05 (0.09)	0.935
Cadence [spm]	167.44 (7.95)	167.42 (8.30)	0.02 (4.11)	0.983	0.75	166.63 (7.69)	165.70 (8.20)	0.93 (5.01)	0.970

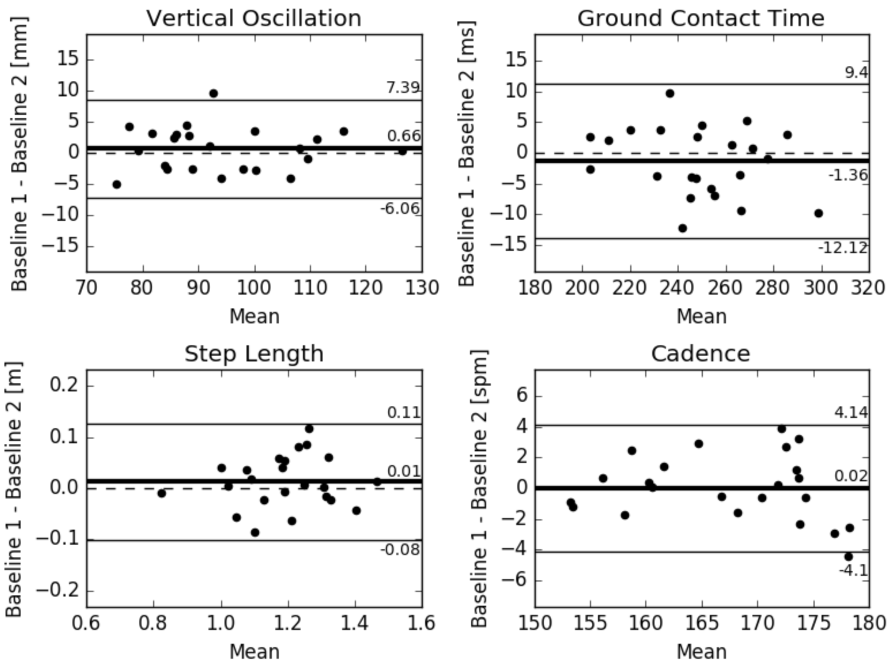

Figure 2: Bland-Altman plots for reliability for the variables Vertical Oscillation, Ground Contact Time, Step Length and Cadence. The black line is the mean difference, and the full lines are the 95% limits of agreement for the mean difference.

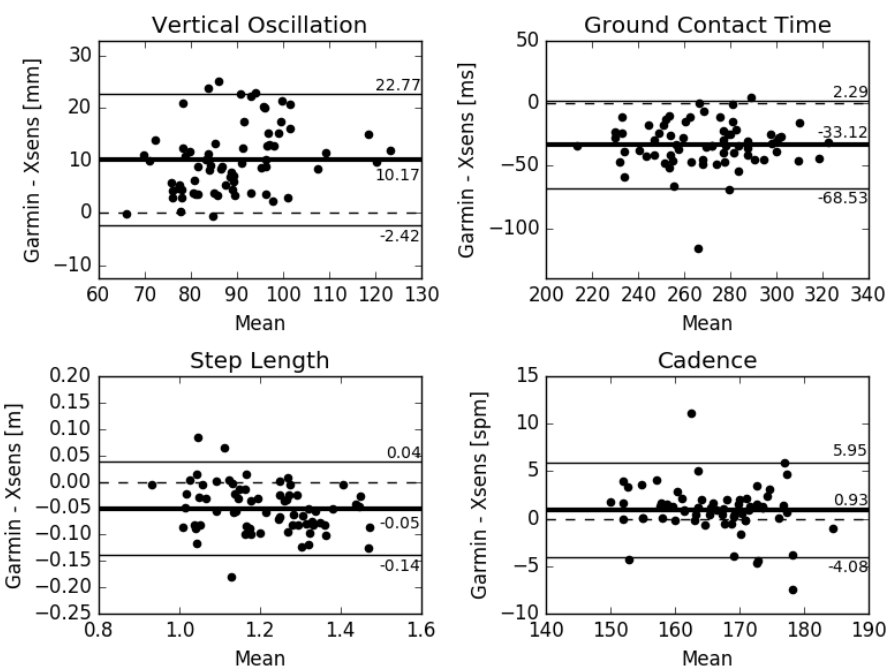

Figure 3: Bland-Altman plots for validity for the variables Vertical Oscillation, Ground Contact Time, Step Length and Cadence. The black line is the mean difference, and the full lines are the 95% limits of agreement for the mean difference. This plot contains differences between methods for the 10, 12 and 14 km/h running trials.

Discussion

The purpose of this study was to test the reliability and validity of the Garmin Forerunner 735XT by comparing the running dynamic variables: Vertical Oscillation, Ground Contact Time, Step Length and Cadence collected by the Garmin watch against the full body kinematic data from an Xsens MVN Link motion capture system in-field. The test re-test reliability for all four variables was evaluated as good with ICC(2,k) values ranging from 0.968 to 0.987 and concurrent low SEM values. In addition, Bland-Altman analysis revealed a narrow LoA range for all four running dynamics variables between baseline trials. The validity was evaluated as good for VO, SL, and Cadence, while moderate for GCT. However, Bland-Altman analysis showed that the GFR overestimated VO while underestimating GCT. This study is the first of its kind to test the reliability and validity of the running dynamics of commercially available activity tracker in-field. Furthermore, this study is the first to include Stride length. Previous studies have not been able to validate this variable since the activity tracker rely on GPS to estimate stride length, which is not obtainable on a treadmill.

The test re-test reliability results are similar to previous findings for VO, GCT, and Cadence in a laboratory setting (Adams et al. 2016). In this study, controlling the speed between baseline trials during in-field testing was challenging. Even though the speed was measured with a Garmin Fenix 2 watch, it was difficult to maintain the speed during the entire trial. As a consequence, a mean absolute difference of 0.43 km/h was observed between trials, and therefore the authors can not eliminate the possibility that differences between baseline trials might be due to changes in running dynamics and not measurement error. In addition, subjects could have experienced a warm-up effect or fatigue effect that might have influenced the test re-test results. In spite of this, these findings indicate that the GFR can be used to estimate running dynamics reliably in-field. Furthermore, the SEM values provide knowledge of how much change is needed in each variable to detect actual changes in running dynamics. Therefore, these SEM vales can be used as the measurement error in-field and as guidelines for individuals wishing to increase or decrease a particular running dynamic variable.

Good agreement for VO was found between the GFR and Xsens. This is consistent with Watari et al. (2016) and Adams et al. (2016) validating similar devices compared to kinematic measures. Noticeably, the ICC value in this study is considerably lower than these studies. In addition, Bland-Altman analysis showed that the GFR systematically overestimated VO and the 95% LoA revealed considerable variability between methods. This might be attributable to the comparison between a single segment of the heart rate strap against an estimation of the COM of the Xsens data. Gard et al. (2004) found that estimation of VO using a single marker significantly overestimates VO compared to a segmental analysis method and the golden standard kinetic method. Similarly, Watari et al. (2016) found excellent agreement between a similar device and the single marker method, while only moderate agreement between the device and the golden standard kinetic method. Based on the results of this study, the VO from the GFR needs to be interpreted with caution.

The validity for GCT was found to be moderate. However, Bland-Altman analysis revealed that GFR underestimated GCT and large variability exists between methods. These findings might be explained by the algorithm used to calculate the GCT from the Xsens data. The algorithm used in the current study was suggested by Dingwell et al. (2001). The algorithm was done for walking on a treadmill and have been shown to overestimate GCT during running (Smith et al. 2015). In future studies, more precise algorithms should be used to calculate GCT to evaluate the validity of GCT estimate by GFR. Several algorithms rely on the use of heel- and toe-marker to calculate GCT (Smith et al. 2015). In this study, no marker data for the heel or toe was obtained, and thus alternative algorithms were considered. The Dingwell algorithm was chosen in this study since it was the best fit for the data collected. With this in mind, it could explain the difference between the GFR and Xsens data. Another algorithm for calculating the GCT of the Xsens data should be developed, before a more reliable assessment can be made of the GCT validity.

The ICC(2,k) showed good agreement for SL between the two methods. Similarly, Bland-Altman analysis revealed a slight underestimation of the SL for GFR compared to the Xsens data. In this study, the position of the foot during heel strike was used to calculate the SL, a measurement unobtainable by the GFR. It is unknown which algorithm the GFR uses to calculate SL. Therefore, the underestimation could be due to slight differences between algorithms. However, due to a high ICC value, low variability between methods and despite a slight underestimation, the GFR is considered valid for estimating SL.

Cadence showed the most promising results with the highest ICC(2,k) value, a negligible mean overestimation and a narrow LoA range between methods. The slight differences between methods could be contributed to errors in the data processing algorithms. The cadence based on the Xsens data were found for each heel strike. However, since only 60 seconds of data were used, a cut-off might have occurred during a step. Therefore, if the last step was cut-off it was excluded from the data set. As a consequence, the cadence calculated from the Xsens data is the amount of full steps per minute. This could contribute to the slight differences between methods, and the true difference could be even smaller. GFR was found to produce a valid estimate of Cadence.

This study provides information about the reliability and validity of a commercially available activity tracker. Moderate to good agreement were found for all variables, which provide evidence that the Garmin Forerunner can provide a reliable and valid estimate of the running dynamic variables used in this study. However, due to the large differences found between methods for GCT and VO, a problem could arise if the GFR is used to pursue a specific value for one of the two running variables or for clinicians using the device to analyze running style. It could be argued that as long as the device is reliable it can provide the users with sufficient feedback to modify the running dynamics and thereby be used in gait re-training.

Future studies should focus on validating the commercial available activity trackers stride to stride variability for the running dynamic variables. Further, another algorithm for calculating the GCT should be developed by identifying specific gait events in the Xsens data. Thereby, a more reliable validation of GCT can be made in-field.

Conclusion

The Garmin Forerunner XT735 is a reliable and valid alternative to expensive specialized equipment for estimating running dynamics in-field. Garmin Forerunner XT735 can be used by runners, coaches, and clinicians to assess and monitor running dynamics in-field. However, the estimate for Vertical Oscillation yield a systematic overestimation and the Ground Contact Time yield a systematic underestimation compared to full body kinematics. Therefore, these variables should be interpreted with caution.

Acknowledgements

The authors would like to acknowledge Mark de Zee and René Børge Korsgaard Brund for supervision and guidance. Furthermore, thanks are due to Anderson de Souza Castelo Oliveira for help with data processing and the subjects for participating. The authors had no commercial interest or financial backing from any of the manufacturer or suppliers used in the present study.

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