Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 147 (2016) 573 – 577
Procedia Engineering
www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

Intra and inter test repeatability of accelerometric indicators measured while running

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Abstract

Recently the use of Inertial Measurement Units (IMU's) has been extended to several applications in human activity. In running, several studies show the possibility of using IMU's to measure different indicators of speed and foot strike. However, few studies describe the repeatability of those indicators. In this context, the aim of this study is to analyse the intra and inter test repeatability of several temporal and spectral indicators using an IMU under constant running conditions. Accelerations were measured using three IMU's mounted on the trunk near the lumbar, the right tibia and the dorsal surface of the right shoe above the metatarsals. The subject follows two different protocols to realize the intra test and the inter test repeatability of eight different parameters: root mean square (RMS) values of acceleration, kurtosis, total energy, median frequency, mechanical stiffness, mean stride duration, contact and flying duration. For all parameters the mean, standard deviation and coefficient of variation were computed for each set of test. The coefficient of variation was lower than 5% for both test for all parameters except kurtosis and the median frequency. Parameters with acceptable value at constant conditions of surface and speed can be used as an indicator to compare several conditions, such as the influence of speed, surface or anthropometry of the subjects.

Peer-review under responsibility of the organizing committee of ISEA 2016

Keywords: Inertial measurement units, Running, Repeatability, Accelerometric indicators

1. Introduction

The measures of accelerations give important information in biomechanics and particularly in sports for the analysis of movement, shock and vibrations. These measurements have been useful to study forms of locomotion like walking [1], running [2][3], and jumping [4] and to distinguish the intensity levels in those movements [5]. In running, accelerations can represent the shock waves propagating through the human locomotor system. Accelerometric measures are recorded using industrial accelerometers requiring cables and acquisition system. The alteration created by the use of these equipments limit the possibilities to study the movement of an athlete. The use of accelerometric data as a source of information in sports has been expanded recently thanks to the use of Inertial Measurement Units

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Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.242

(IMU's). The IMU's are presented as an alternative that allow in-the-field performance monitoring without constraining athletes' movements. This device has as advantages its low weight, the possibility to be portable and wearable, that it can be used in field conditions and that it can facilitate extended data collection. Because of these characteristics, the use of this device has been extended to several applications in human activity and to develop commercial wearable systems.

In running, the IMU's have been used to measure the vertical acceleration at the center of mass [6], to identify foot-strike and foot-off instants; to estimate the stance, steps and stride duration in sprint [7], or with a variation of running speeds [1][8][5]; to identify foot-strike pattern [9], to evaluate running asymmetry [10] and to measure stride-by-stride running speed [11]. IMU's placed in the lumbar spine have been used also to isolate every stride [12][13] and to identify the flight duration, contact duration and stride duration. Upon these parameters, the mechanical stiffness can also be calculated [4][14][15].

In order to use a sensor, it has to be validated by a reliability test. In this case, the study of Henriksen et al. in 2004 [1] determine the test-retest reliability of a trunk accelerometric gait analysis in healthy subjects for walking. This reliability is analysed taking as indicators the root mean square value of accelerations, cadences, step and stride lengths for different walking speeds. The results of that study show high interclass correlation and a low measurement error (under 0.01g for mean acceleration).

Thus, several parameters are used in the analysis of running by IMU's, however little is known about the repeatability of these parameters for one subject. The purpose of this study is to test eight parameters extracted from the IMU's accelerometric signal to analyse their inter and intra test repeatability in running while the conditions of speed and surface are constant. Those parameters are computed in the temporal and frequency domains.

This paper is divided in four sections. First, the materials and methods establishing the two protocols and the definition of the parameters. Second, the results of the eight studied parameters are presented in terms of coefficient of variation. Third, a discussion is made over the repeatability of the studied indicators. Finally, a conclusion is made on this study presenting possible future work.

2. Materials and methods

2.1. Subjects

One healthy man was recruited for this test (22 years old, 173cm, 76kg). The subject volunteered to participate in the study, which was approved by the local university ethics review board and was in agreement with the declaration of Helsinki. The volunteer was aware of the purpose of the study and he provided written informed consent. The subject was recreational runner with a training frequency of 2 or 3 times per week and was chosen for his constant practice of running.

2.2. Equipment and data acquisition

The running test was performed on a treadmill (NordiTrack C300). The subject was equipped with three IMU's Hikob Fox (Hikob, Villeurbanne, France) composed of a tri-axial accelerometer. The first one was placed on the foot on the dorsal surface of the right shoe above the metatarsals (Fo). The second was mounted at the centre of mass of the leg, according to the anthropometric data described by Winter [16], on the bony part of the tibia (Ti). The last one was placed on the trunk near the L4-L5 space of the lumbar on the line between the two iliac crests, with one axis of the IMU was aligned with the vertical axis of the body (Lu). The acquisition was made with a sampling frequency of 1344Hz with maximum magnitude of ±24g for the foot and the tibia devices, and ±8g for the lumbar device. The shoe device was mounted on the lace, held in the eyelets of the housings. Tibia and lumbar devices were maintained with a Velcro strip, made for the test. All raw data were logged on a memory card. The three IMU's were synchronized by the use of a radio frequency remote control.

2.3. Protocol

The test was divided into two sequences of ten measures spaced by one day. Before each sequence the subject was asked to warm up by performing two minutes of walking followed with five minutes of running at 12km/h. The two sequences were composed of ten measures of one minute running at 12km/h with one minute rest between measures. In the first sequence the intra test repeatability was analysed without removing the IMU's. In the second, the IMU's were removed and reinstalled on the subject during time of rest to analyse the inter test repeatability.

2.4. Data analysis

First the total acceleration A was determined for each IMU's, defined as the square root of the sum of the squared axis acceleration A_x,A_y,A_z (Eq. 1).

$$A = \sqrt{A_x^2 + A_y^2 + A_z^2} \tag{1}$$

Then, eight indicators were computed, divided in two groups. First, indicators measured on the raw signal that are easy to carry on for a statistical point of view. Then, indicators that are present in running literature but that consider an important signal processing.

Four of them were associated to the stride and were computed only for the vertical axis of the lumbar. Each stride was isolated following the method described by Cavagna in 1970 [12] and then generalized [13] where the vertical acceleration during the flying time is inferior to zero. For each stride, the flying duration (defined as the duration were the vertical acceleration is inferior to zero), the contact duration (defined as the duration were the vertical acceleration is superior to zero), and the stride duration (computed as the sum of the flying and the contact duration) were computed. Then for the raw signal the mean flying duration (MFD), the mean contact duration (MCD) and the mean stride duration (MSD) were determined on the average value for all the strides. The last indicator was the mechanical vertical stiffness (MSf) based on the MFD, the MCD and the mass of the subject as described by Delleau et al. [4] for hopping exercise and generalized for running with different sensors [14][15].

Two indicators were computed for the raw signal in the temporal domain, determined from the total acceleration of the lumbar, tibia and foot devices. The first indicator was the Root Mean Square (RMS) value, defined for a discrete acceleration $A(n)$ of N samples by (Eq. 2). This indicator is used to characterise the magnitude of a varying signal, such as vibration and shock. The second temporal indicator was the kurtosis (Ku) defined for $A(n)$ of N samples and with a mean value μ by (Eq. 3). Ku characterises shock and represents how much data are peaked or flat. This parameter is highly used in mechanical applications where there is presence of shock and it could be used in the study of running.

$$RMS = \sqrt{\frac{1}{N}\sum_{n=1}^{N}[A(n)]^2} \tag{2}$$

$$Ku = \frac{\frac{1}{N}\sum_{n=1}^{N}[(A(n)-\mu)^4]}{(\frac{1}{N}\sum_{n=1}^{N}[(A(n)-\mu)^2])^2} \tag{3}$$

Two indicators were computed in the frequency domain. First, Hanning window was applied on all the point composing the raw signal, then a Fast Fourier Transformation (FFT) was used to compute the frequency signal. The two frequency indicators were determined for the total acceleration of the lumbar, tibia and foot devices. The indicators were the total energy (TEn) of the spectrum defined as the sum of the squared FFT and the median frequency (MdF) defined as the frequency dividing the spectrum in two regions with equal energy.

Finally for each sequence of ten measures and each indicator, the mean, standard deviation (std), and Coefficient of Variation (CV) were computed to judge the inter and intra-test repeatability of these indicators. Indicators were considered repeatable for both inter and intra-CV less than 5%. Using a Shapiro-Wilk's test it is found that the data does not follow a normal distribution. Mann-Whitney statistical test was used to evaluate the difference between the results obtained from the two protocols.

3. Results

Taking into account the eight indicators and three points of measure, sixteen parameters were measured in this study. The mean, standard deviation and coefficient of variation of those parameters are indicated in Table 1.

Table 1. Intra and inter repeatability for the different indicators. Bold values represent unacceptable indicators. Results are presented as mean±std (CV). (*) Significant difference between intra and inter test.

Indicator	Point	Intra Test	Inter Test
RMS [m/s^2] *	Lu	15.85±0.35 (2.2%)	16.36±0.15 (0.9%)
RMS [m/s^2] *	Ti	24.04±0.22 (0.9%)	23.80±0.14 (0.6%)
RMS [m/s^2] *	Fo	43.58±0.85 (1.9%)	43.06±0.62 (1.4%)
Ku *	Lu	**1.77±0.27 (15.0%)**	**2.49±0.17 (6.7%)**
Ku	Ti	**3.08±0.50 (16.4%)**	**4.50±0.88 (19.5%)**
Ku *	Fo	**12.06±2.08 (17.3%)**	**20.85±2.03 (9.7%)**
TEn [(m/s^2)^2] *	Lu	1204.50±55.17 (4.6%)	1267.83±24.68 (1.9%)
TEn [(m/s^2)^2] *	Ti	3008.31±51.36 (1.7%)	2955.27±35.65 (1.2%)
TEn [(m/s^2)^2] *	Fo	9019.94±348.39 (3.9%)	8785.70±219.28 (2.5%)
MdF [Hz]	Lu	2.67±0.02 (0.9%)	2.67±0.02 (0.9%)
MdF [Hz]	Ti	**6.22±0.84 (13.6%)**	**6.28±0.81 (12.9%)**
MdF [Hz]	Fo	**7.70±0.83 (10.7%)**	**8.62±0.62 (7.2%)**
MSD [s]	Lu	0.375±0.001 (0.4%)	0.376±0.002 (0.6%)
MCD [s] *	Lu	0.178±0.002 (1.1%)	0.180±0.002 (1.1%)
MFD [s]	Lu	0.196±0.002 (0.9%)	0.195±0.002 (0.8%)
MSf [N/mm]	Lu	37.88±0.61 (1.6%)	37.29±0.68 (1.8%)

As shown in the table, the CV was lower than 5% for both test for the RMS and the TEn for all three devices. The MdF presents a repeatable value only for the acceleration measured at the lumbar position. On the contrary, the Ku presents a high coefficient of variation for both the inter and intra test for all the device positions.

For the parameters depending on the stride that were measured only at the lumbar position, all of them were proven acceptable in the inter and intra test.

A statistical test show that several indicators present a significant difference between the intra and inter test.

4. Discussions

First, results of this study present a significant difference for several indicators between the intra and inter test. This difference allows to conclude that is not possible to compare one subject for two consecutive day. However this observation does not have impact on the separated results of the intra and inter test repeatability.

This study shows that indicators associated to the quantity of energy as RMS and TEn are repeatable under constant condition of test. An explanation for this could be that the overall acceleration of each segment is constant.

Other indicators, such as MdF, present an acceptable CV values only for the lumbar. This could be due to the energy and shock absorption by the different segment of the human body. Indeed, IMU's at the foot and tibia, show multiple harmonics and so a more distributed energy, for the lumbar IMU, the shock is attenuated through the body and the energy is present specifically for the fundamental frequency. However the MdF gives only limited information and present an excessive sensitivity to the energy repartition through the harmonics.

Indicators associated to the different phases of running cycle (MSD, MCD, and MFD) can be identified by the use of one accelerometer and show a great repeatability ($<$2%). The capacity to determine precisely these indicators, presents an important advantage for the IMU. These results show that an accelerometer allows to measure and detect specific running event as presented on the study of Buchheit et al. [15]. Moreover, these indicators show a great repeatability for constant condition of test and can be used for more complex studies involving variable speeds and different subjects.

As expected, MSf based on indicators associated to running phase is repeatable. These results are in accordance with the study of Pappas et al. [17] that study the reliability of the MSf using a high-speed video camera, and allow to validate the use of IMU's for the computation of this indicator.

Finally, Ku presents poor and unacceptable CV's for the three devices. This may be due because Ku is not repeatable under constant condition, or maybe because the IMU does not allow the measurement of shock and peak precisely, maybe due to a limitation of the IMU.

Unrepeatable indicators at constant condition of surface and speed should be used carefully for studies with variable condition. Indeed, a significant difference between two different conditions (for example two different speed) could be biased because the indicator is unrepeatable for a same and constant condition.

5. Conclusion

These results show several indicators that have a repeatable measure using IMU's and could lead to studies of the influence of the speed, the ground surface or the anthropometry of the subjects. This study presents advantages for the use of IMU's as the possibility to measure indicators associated to the running phase, but also maybe a limitation to measure the intensity of peak and shock.

Acknowledgements

These investigations are financially supported by the Champagne-Ardenne region and by The European Fund of Regional Development (FEDER). The authors wish to thank neXXtep Technologies for their contribution.

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