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Descriptive analysis of 3D foot motion using inertial sensors: comparison between lower extremities

Análisis descriptivo del movimiento 3D del pie mediante sensores inerciales: comparación entre extremidades

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Keywords:

Inertial sensor, accelerometry, 3D kinematics, foot motion.

Abstract

Objectives: The objective of this study is twofold, on the one hand, it is to make a kinematic description of the movement of the foot in the three planes of the space and, on the other hand, to determine if there are differences between the lower extremities.

Patients and methods: The study is a descriptive, observational and cross-sectional one, with a sample consisting of 40 healthy adults who are also regular runners. The assessment protocol consisted of running on a treadmill at a speed of 9 km/h. Data collection was carried out during the first 20 seconds, after which the speed of the treadmill was stabilized.

Results: In the dorsi-plantar movement, no significant differences between feet were found ($p<0.37$), whereas in the pronation-supination movement and the abduction-adduction movement significant differences were found, especially in the right foot ($p < 0.002$ and $p < 0.02$ respectively). The size of the effect in the movement in the sagittal plane was found to be very small, while in the frontal and transverse planes it increased to a medium effect.

Conclusion: During running, the foot follows a logical sequence of movements. While no significant differences exist in the dorsi-plantar movements, in the pronation-supination and abduction-adduction movements the right foot was found to have a bigger range of movement than the left foot.

Palabras clave:

Sensor inercial, acelerometría, cinemática 3D, movimiento del pie.

Resumen

Objetivos: El objetivo del presente estudio es doble: por un lado, realizar una descripción cinemática del movimiento del pie en los tres planos del espacio y, por otro, determinar si existen diferencias entre ambas extremidades.

Pacientes y métodos: Se trata de un estudio descriptivo, observacional y transversal, con una muestra de 40 corredores habituales, adultos sanos. El protocolo de valoración consistió en carrera sobre cinta rodante a una velocidad de 9 km/h. La recogida de datos se realizó durante 20 segundos, después de estabilizada la velocidad de la cinta.

Resultados: En el movimiento de flexión dorsal-flexión plantar no se observan diferencias significativas entre pies ($p < 0.37$). En el movimiento de pronación-supinación y en el de adducción-abducción sí existen diferencias significativas, siendo mayor en el pie derecho ($p < 0.002$ y $p < 0.02$ respectivamente). El tamaño del efecto es muy pequeño en el movimiento en el plano sagital, mientras que en los planos frontal y transverso es un efecto mediano.

Conclusión: Durante la carrera el pie mantiene una secuencia lógica de movimiento. Mientras no existen diferencias significativas en los movimientos de flexión dorsal-flexión plantar, en los movimientos de pronación-supinación y adducción-abducción el pie derecho tiene mayor rango de movimiento que el pie izquierdo.

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INTRODUCTION

Inertial measurement units (IMU) are portable devices which, by using a combination of accelerometers, gyroscopes and magnetometers, can be used to determine kinematic patterns carried out in any environment, including the real environment of a runner, and are an alternative to the current laboratory-based research[1-3].

Due to their small size and wireless properties, IMUs allow for the movement to be studied without restrictions. Some studies have shown that they are able to detect the changes in running biomechanics with precision and can help to determine injury factors due to mechanical overload[4,5]. A variety of researchers have used accelerometers placed on the participant's sports footwear to measure changes in running; Boutaayamou et al.[6] validated the use of two accelerometers, fixed on each shoe at the level of the heel and the proximal part of the big toe, against a conventional three-dimensional (3D) optical analysis system without finding significant differences between the two methods.

Other studies have shown evidence for asymmetry of movement during walking. For instance, Mayolas et al.[7] observed an asymmetric walking behaviour, independent of the laterality of the subjects, in a child population. The results did not reveal significant bilateral differences in the general plantar pressure, but the majority of the children were found to not only apply a higher pressure in the right hindfoot rather than in the left hindfoot, but also to do so in the midfoot and left forefoot rather than in the right forefoot.

In addition, Niu et al.[8] found that plantar pressure could be used to evaluate the foot's stability. In comparison to the non-dominant side, the dominant foot was seen to be more secure when in a single-foot stance due to the higher total contact area. This was especially true in an ankle inversion stance, due to a higher antero-posterior force ratio.

Thus, the scientific interest in the analysis of the foot movement has been on the rise with the objective of reducing the risk of injury and improving running efficiency and performance. However, there is a lack of studies which attempt to describe kinematic patterns with the use of IMUs. The objective of this study is twofold. On the one hand, it is to make a kinematic description of the movement of the foot in the three planes of movement and, on the other hand, to determine if there are differences between both extremities. The null hypothesis establishes that there are no differences between feet.

PATIENTS AND METHODS

This is a descriptive, observational and transversal study approved by the University of Vic – Central University of Catalonia's Ethical Committee, following the principles of the Declaration of Helsinki.

The sample was composed by 40 male adults (ages 43 ± 13.8 years, height 175.5 ± 7.07 cm, weight 72 ± 5.5 kg) without any alterations in their locomotor system. All of them gave their written consent prior to the evaluation.

A running treadmill (BH Fitness G6414V SPORT, Álava, Spain) was used to capture various running cycles. It has been previously observed that running on a treadmill is representative of overground running[9,10].

Two IMU units, equipped with a triaxial accelerometer, gyroscope and magnetometer (MotionPod, size 31 × 21 × 15 mm and a weight of 14g, Grenoble, France), software BioVal (RM Ingénierie. Rodez, France)[11,12] and a wireless interface (2.4 GHz, transmission range of up to 30 m, ≈ 8 h of usage, sampling rate of 30 Hz) were used to collect the data. The data from the apparatus was transferred to a PC through a USB device.

Each participant warmed up on the machine by running for three minutes at 9 km/h (2.5 m/s) in order to familiarize themselves with its speed and the environment.

Once the warming-up period was completed, the athlete rested for two-minutes and the experimental procedure was explained.

The sensor was placed in the instep of the subject's footwear using Velcro and secured with adhesive tape in order to reduce the device's vibrations (Figure 1).

Each participant wore their own footwear. It has been observed that changes in midsole hardness affect lower-extremity kinematics[13]. The same footwear had to be used in the two evaluated conditions.

According to the manufacturer's protocol, the subject had to first remain still in an upright position for three seconds whilst data from both feet was being registered.

After the preparation, each participant's running was recorded for 20 seconds at the same previous speed of 9 km/h. The data began being collected once the treadmill had stabilised at the set speed.

Angular displacement data was measured between the maximum and minimum angular points in the sagittal plane (foot dorsi-plantar flexion), the transversal plane (abduction-adduction), and frontal plane (pronation-supination). Explanatory note: The manufacturer introduces the concept of pronation-supination when, in reality, based on the podiat-

Figure 1. Left: Image of the sensor used in this study. Right: Initial position of the participant on the running treadmill, with the sensor fixed on the footwear. Author's source.

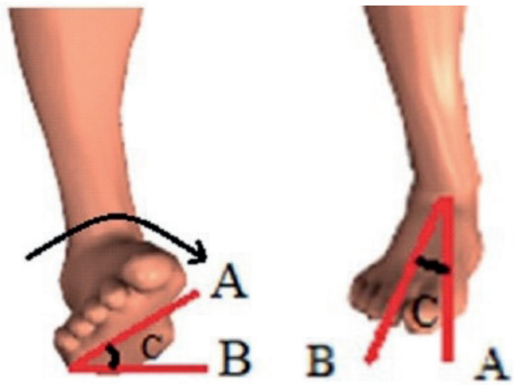

Figure 2. Left: Pronation movement of the foot. Line A indicates the supination plane, and line B indicates the plane of the ground. Right: Abduction movement of the foot. Line A indicates the sagittal plane, whilst line B indicates the foot's direction. Author's source.

ric definition, it should be inversion-eversion. This is because eversion is a movement on the frontal plane where the midfoot zone approaches the plane of the ground, and inversion is a movement on the frontal plane where the midfoot zone separates from the ground plane, whereas pronation is a triplane movement of flexion, eversion and abduction and supination is a combination of inversion, adduction and plantar flexion[14] (Figure 2).

The data was exported to an Excel spreadsheet for further analysis. Normality of the data was analysed using Shapiro-Wilk test. For the comparison of means, the Student's *t*-Test was performed with a confidence interval of 95%, recognizing those values with a p-value of less than 0.05 as being statistically significant. The effect size of the results was calculated using the Cohen test ($d \leq 0.2$ negligible, $0.2 \leq d \leq 0.5$ small, $0.5 \leq d \leq 0.8$ medium o $d \geq 0.8$ large effect)[15,16].

RESULTS

Extremities comparison

The results are displayed in Table I. The differences between the amplitude mean of the left and right feet were found to be insignificant in the flexion–extension movement ($p < 0.37$, with a d-Cohen effect being barely perceived). In contrast, the differences between the amplitude mean in the latero-medial movements (abduction–adduction) and in the pronation–supination movements were statistically significant, with p-values $p < 0.02$ and $p < 0.002$, and with medium effect sizes of 0.48 and 0.55, respectively. The higher values were observed in right foot.

Description of the curves

Figure 3 shows the angular displacement of the foot for a running cycle in the three axes of movement.

- **Dorsal flexion-Plantar flexion:** The running cycle starts on the point of maximum dorsal flexion, descending towards the X axis and drawing a slight plateau shape during the middle stance before turning into a plantar flexion. In the swing phase, the transition to a flexion is produced.
- **Abduction-adduction:** In the stance phase, at the touchdown point, the foot is parallel to the X axis, drawing a plateau shape during the middle stance and descending into abduction during the impulse phase. In the swing phase, the movement changes to adduction, and this is maintained throughout the phase until the touchdown (Figure 2).
- **Pronation-supination:** The touchdown begins at the point of minimum pronation of the curve, ascending towards the X-axis towards maximum pronation and drawing a plateau shape during mid-posture. The curve shows a discrete supination during the impulse phase. In the swing phase, the pronation curve changes to supination and the foot is positioned for the initiation of contact.

DISCUSSION

The first aim of this study was to kinematically describe the amplitude of the 3D movement of the left and right feet in a complete running cycle. The curve analysis has led to the observation that the foot movement follows a logical sequence; that is, in the stance phase the start of the extension of the foot coincides with the start of pronation, the foot's stabilization occurs parallel to the X axis, and in the elevation of the heel during the propulsive phase (leverage phase) the foot carries out an abduction. In the swing phase, the foot

Table I. Mean and standard deviations of angular displacement for each extremity. Values in degrees (º). *Statistically significant differences as p<0.05.

	Left foot	Right foot	Student's t-test	Cohen's d test
Dorsi-Plantar Flexion	94.9 ± 12.5	93.8 ± 13.5	p < 0.37	0.07
Pronation-Supination	16.4 ± 5.0	19.2 ± 4.8	p < 0.002*	0.55
Abduction-Adduction	22.4 ± 7.5	26.4 ± 9.0	p < 0.02*	0.48

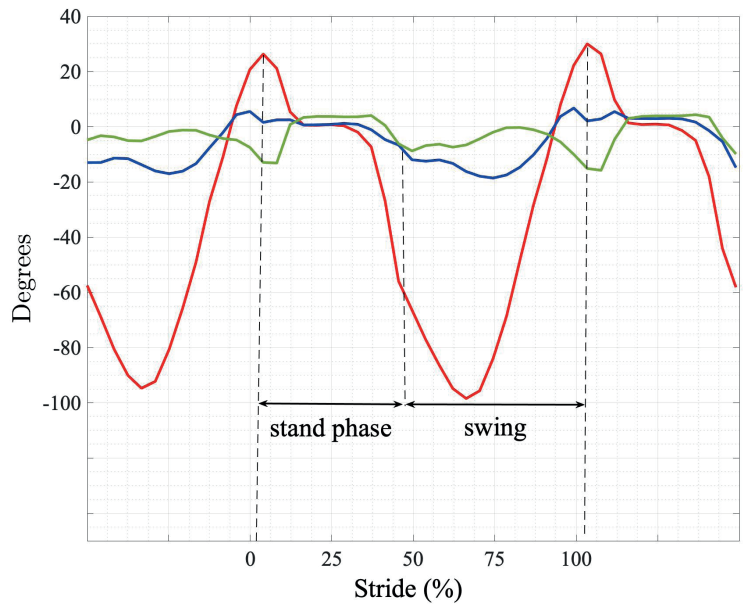

Figure 3. Graphic of the angular displacement of the foot in a running cycle. The legend on the lower left indicates the direction of the movement. Author's source.

combines flexion, inversion and adduction. Combining these 3D movements during the stance phase is crucial to establish the unipedal balance, and in the swing phase, the combination of the 3D movements place the foot correctly for the start of the new running cycle.

The second objective study was to assess whether differences between the movement of the feet were present. Although the results of the study do not reveal significant differences in the dorsi-plantar flexion, a bigger amplitude of movement has been observed in the frontal plane with an eversion movement more pronounced in the right foot. Therefore, the null hypothesis could be rejected. This could suggest that since the sagittal plane is the plane of reference, the alternation of support between the feet does not alter the mechanics, however, eversion movement is more pronounced in the right foot, meaning that it tends to have higher degrees of inversion at the start of contact than the left foot.

When it comes to the abduction movement, it is also more pronounced in the right foot, which could suggest that higher pronation implies higher abduction too, since the foot is a segment that does not execute pure movements but instead carries out combined movements.

As a matter of fact, these movements are not pure, as mentioned before, but are instead combined, since the ankle joint and the tarsal joints are mechanically associated through the subtalar axis. Their oblique projection allows for the movement of the tibia to be linked with the combination of movements from the foot. For example, in a stance phase, the internal rotation of the tibia generates a pronation movement on the foot, and similarly an external rotation of the tibia leads to a supination movement of the foot[17].

We have not found any studies that compares angular displacement mechanics between the limbs, although other studies have found differences between extremities using other types of mechanical variables. Cowley[18] analysed the change in height of the navicular bone in 30 runners (12 women and 18 men) after running 21 km, and found a significant lowering of the foot arch in both feet (4.2 mm in the left foot and 5.0 mm in the right foot). The study thus showed a change in foot posture, with a descent of the medial arch (this effect being more pronounced in the right foot) but did not explain the reasons for this change.

Stodólka et al.[19] examined the level of bilateral symmetry between the trajectory of the centre of pressure (CoP) of the left and right feet in the lateral-medial and antero-posterior directions. On the one hand, it was observed that 88% of the participants displayed symmetry in both feet for the magnitude and direction of the antero-posterior trajectory of the CoP, but on the other hand, asymmetry was observed in 67% of the participants for the latero-medial trajectory; CoP displacement was noted along the lateral limit of one foot and along the medial limit of the other. Similarly, Muntanyola[20], in a study on 663 subjects, discovered that the displacement, range and velocity of the CoP in the antero-posterior axis were bigger than in the latero-medial axis, and the majority of the subjects also showed a higher pressure on the right foot.

Rai et al.[21] registered footprints in 66 subjects, with and without a pathology, using an electronic pedobarograph. The results showed an asymmetric distribution of the plantar pressure in the right and left feet of the subjects without a pathology (17 % had the same pressure on both feet, 7 % had higher pressure on the left foot, and 76 % pressure on the right foot).

Thus, it seems that scientific evidence exists where certain values have been found to be significantly different or higher in the right foot compared to the left foot. The results presented in this study also seem to support this trend. It is of our thinking that the condition of laterality must have some influence in this. For instance, Hardyck[22] suggested that a preference on the use of the left hand, ranging from moderate to strongly left-handed, would be found on approximately only 10 % of the population. Nevertheless, a left-handed population should be studied before this link can be confirmed.

We regard that this pattern of movement should be considered to be normal, although it is true that any deviation from the averages observed in the movements in the frontal and transverse planes, would be susceptible to generate imbalances and, consequently, pathology in the locomotive system.

One limitation of our study was that we did not evaluate neither the laterality nor lateral dominance of the subjects, two different concepts following Carpes et al.[23], not being able to know if the differences observed are due to the predominance of right-handed or right-leg dominant population. Further studies are needed to assess correlation between kinematics and lateral dominance. It is also suggested to increase the number of subjects to corroborate and validate these results.

In conclusion, the results obtained in the present study did not show statistical significant differences in the range of motion between both feet in the sagittal plane, while significant differences were found in the frontal and transverse planes. Differences are more noticeably on the right right foot in a samlpe of normal healthy runners. This study show a logical kinematic pattern in the movement of the foot and, despite the asymmetry observed between limbs, the values for this running speed must be considered to be normal.

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CONFLICT OF INTERESTS

Authors do not have any conflict of interests.

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