Biomechanical Parameters of Foot Function Measured in the Office of a Specialist in Orthopedics and Traumatology

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ABSTRACT

Introduction: Dynamic studies of foot function are usually carried out in highly complex gait analysis laboratories. The objective of this study was to analyze functional parameters using a force platform in a series of asymptomatic patients evaluated in an outpatient clinic. **Materials and Methods:** Cross-sectional study, which included a consecutive series of volunteer asymptomatic patients who underwent a force platform measurement (TekScanMatScan®, Boston, MA, USA) between 2014 and 2020, in the City of Buenos Aires, Argentina. **Results:** 316 records were included, corresponding to 158 individuals with bilateral measurements. Most were women (66.5%), with a mean age of 47 years (SD 16.1). Fourteen variables were evaluated, corresponding to parameters of force, trajectory, and contact time. The total contact time was 0.79 seconds (SD 0.09), and the COF time according to the region of the foot was 20% in the heel, 26% in the midfoot, and 46% in the forefoot. The CPEI (Center of Pressure Excursion Index) value was 16.55% (SD 7.14). **Conclusion:** Foot functional parameters in asymptomatic patients are presented. The contact time of the foot on the ground, the force in the heel, midfoot, and forefoot, and the force trajectory were measured. No ionizing radiation was used. These findings could be used as reference values to detect pathological gaits.
Keywords: Force; center of force; biomechanics; gait analysis; force trajectory; ground reaction force.
Level of Evidence: II

Parámetros biomecánicos de la función del pie medidos en el consultorio del especialista en Ortopedia y Traumatología

RESUMEN

Introducción: Los estudios dinámicos de la función del pie habitualmente se realizan en laboratorios de marcha de gran complejidad. El objetivo de este estudio fue analizar parámetros funcionales utilizando una plataforma de fuerza en una serie de pacientes asintomáticos evaluados en consultorios externos. **Materiales y Métodos:** Estudio de corte transversal que incluyó una serie consecutiva de pacientes asintomáticos voluntarios a quienes se les realizó una medición con una plataforma de fuerza (TekScanMatScan®, Boston, MA, EE.UU.) entre 2014 y 2020, en la Ciudad Autónoma de Buenos Aires, Argentina. **Resultados:** Se incluyeron 316 registros de 158 pacientes con mediciones bilaterales. La mayoría eran mujeres (66,5%) y el promedio de la edad era de 47 años (DE 16.1). Se evaluaron 14 variables, correspondientes a parámetros de fuerza, trayectoria y tiempo de contacto de la fuerza. El tiempo de contacto total fue de 0,79 segundos (DE 0,09), el *CoF time* según la región del pie fue del 20% en el talón, 26% en el mediopié y 46% en el antepié. El CPEI (*center of pressure excursión index)* fue del 16,55% (DE 7,14). **Conclusiones:** Se comunican los parámetros funcionales del pie en pacientes asintomáticos. Se midieron el tiempo de contacto del pie en el suelo, la fuerza (en talón, mediopié y antepié) y la trayectoria de la fuerza con una plataforma de fuerza. No se utilizaron radiaciones ionizantes. Estos hallazgos podrían ser utilizados como valores de referencia para detectar marchas patológicas.
Palabras clave: Fuerza; centro de fuerza; biomecánica; análisis de la marcha; trayectoria de fuerza; fuerza de reacción de la gravedad.
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INTRODUCTION

The foot is one of the most dynamic structures in the human body. The interplay of forces that allows walking is often underestimated and is generally seen as a sculptured image, as if it were a static structure.[1] The complementary diagnostic studies used usually follow this direction (radiography, computed tomography, magnetic resonance, static impression of the foot on support), but it is not usual to evaluate the biomechanics of the foot, despite its eminently functional nature.[2]

Numerous reports have been published in which plantar pressures were evaluated with baropodometry in both asymptomatic and diseased patients.[3-5] But given the highly variable results, plantar pressure assessments tend to be used mainly in diabetic or neurological patients who are at higher risk of ulceration.[6]

Center of Force (CoF) analysis was introduced by Jameson et al., in 2006 to describe trajectory and contact time. The authors found that there was very little difference between the values of the 3D kinematics measurements with the subjective analyses of four observers. The intra- and inter-observer reliability was very high and the division by areas or regions along the longitudinal axis (hindfoot, midfoot, and forefoot) made it possible to analyze the functioning in each region both in asymptomatic patients and in pathological situations.[7] Chiu and Wang, in 2007, and Hagedorn et al., in 2013, provided evaluations using the CoF velocity and trajectory measurement.[8,9]

Most of the published studies on gait biomechanics were carried out in gait analysis laboratories under ideal working conditions, due to the physical space, the number of capture cameras, the force platform in a space of several meters long and the technology to capture and process data.[2,8-11] However, some functional parameters can be captured with a force platform, quantitatively, in a smaller space, such as an outpatient clinic.[4.12]

Although there are gait measurements with proven validity and reliability that can be added to clinical and imaging evaluation, it is not common practice to have this diagnostic method for foot analysis.[13]

The aim of the study was to analyze the results of functional parameters of gait mechanics during the stance phase of the foot, captured in the outpatient clinic using a force platform in a series of asymptomatic patients.

MATERIALS AND METHODS

A cross-sectional, descriptive study of a consecutive series of voluntary asymptomatic patients who underwent a measurement with a force platform between 2014 and 2020, was carried out in the author's private office, in the Autonomous City of Buenos Aires, Argentina.

The inclusion criteria were: asymptomatic patients who were voluntarily asked to undergo a gait study, regardless of the morphological type of foot. All participants signed the informed consent for confidentiality to use the data for scientific analysis and the request for permission to publish the collected data while maintaining the absolute privacy of personal identity (respecting the Declaration of Helsinki).

The exclusion criteria were: fracture or surgery in the lower limbs in the last six months and neurological diseases.

Baropodometric measurement

For the measurements, a force platform (TekScanMatScan®, Boston, MA, USA) of 5 mm thickness and an area of 46 cm by 37 cm with 2288 sensors (1.4 sensors/cm^2) with a transmission speed of 440 Hertz was used. For data collection, each patient underwent a two-step gait initiation protocol that had proven to be reproducible in other studies.[14] The test was repeated in each patient, five steps of the left foot and five steps of the right foot were measured, with adequate validity and reliability.[15]

A force platform similar to that of the Framingham study protocol[8] was used to assess the movement of the CoF during the stance phase. The center of pressure excursion index (CPEI) represents the trajectory of the force during the stance phase (Figure 1).

The data collection was in charge of two assistants (SG and CO) trained and qualified to obtain quality data. The study was repeated from the beginning if the collection was inadequate or erroneous.

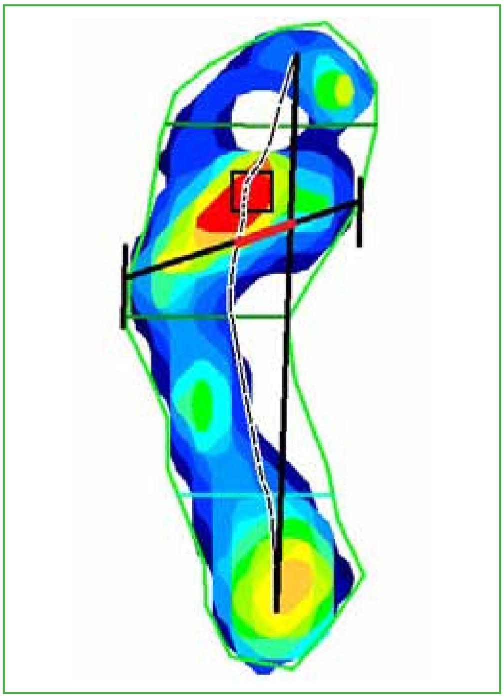

Figure 1. Index of excursion of the center of force measured in %. The center of force is seen on the dotted line. The line of the longitudinal axis is drawn from the starting point of support to the point of toe-off. In the distal third or metatarsal area, a transverse line is drawn that joins both medial and lateral edges of the width of the foot. Then, on this transverse line, the distance between the center of force and the longitudinal line is measured and divided by the total length of the transverse line. The result is the excursion index of the center of force measured in %. In general, the values are positive. The highest values represent supination and the lowest, pronation.

Description of the 3Box system

3Box (TekScan MatScan®) is a computer program that allows dividing the foot into three areas: heel, midfoot and forefoot, discarding the values at the toe level (Figure 2).[12] It measures the reaction force of gravity in relation to time (force/time) and only captures the stance phase of the foot on the ground. It also normalizes force values in percentage of body weight (%BW) in the three regions and describes the trajectory of force (CPEI). The following measurements were taken:

- Contact time (seconds): time elapsed from the first contact of the foot on the floor to the last contact of the same foot (this value is not divided into regions, it takes the whole foot into account).
- CPEI (%): measure of the concavity or medial-lateral deviation of the trajectory of the CoF in relation to the width of the foot. The values are positive.[8]
- *Heel Contact Time* (% contact): Elapsed time from the first contact to the end of the last contact in the heel area, defined by the heel box .
- *Heel Maximum Force* (%BW): Maximum load force during heel contact, defined by the heel box. The value is normalized.
- *Heel Maximum Force* (kg): Maximum load force during heel contact (in kg), defined by the heel box. They are absolute values and are not normalized like the previous one.
- *Heel CoF Time* (time in %) - Time elapsed from the CoF's first contact on the heel until it reaches the anterior limit of the heel box.
- *Midfoot Contact Time* (% contact): elapsed time (in %) from the first contact to the end of the last midfoot contact, where the midfoot is defined between the anterior limit of the heel box and the posterior limit of the metatarsus.

- *Midfoot Maximum Force* (%BW): maximum load force (in %) of body weight during midfoot contact, defined between the anterior limit of the heel and the posterior limit of the metatarsal.
- *Midfoot Maximum Force* (kg): Maximum load force during midfoot contact (in kg), defined by the midfoot area. They are absolute values and are not normalized like the previous one.
- *Midfoot CoF Time* (time in %): time elapsed from when the CoF has just crossed the anterior limit of the heel box until it reaches the posterior limit of the metatarsal box.
- *Metatarsal Contact Time* (% contact): elapsed time (in %) from the first contact to the end of the last contact on the metatarsal, where the metatarsal is defined by the metatarsal box.
- *Metatarsal Maximum Force* (%BW): maximum load force (in %) of body weight during contact time in the metatarsal area.
- *Metatarsal Maximum Force* (kg): maximum load force during contact with the metatarsal (in kg), defined by the metatarsal box.
- *Metatarsal CoF Time* (time in %): elapsed time (in %) from when the CoF has just crossed the posterior limit of the metatarsal box until it reaches the anterior limit of the metatarsal box.

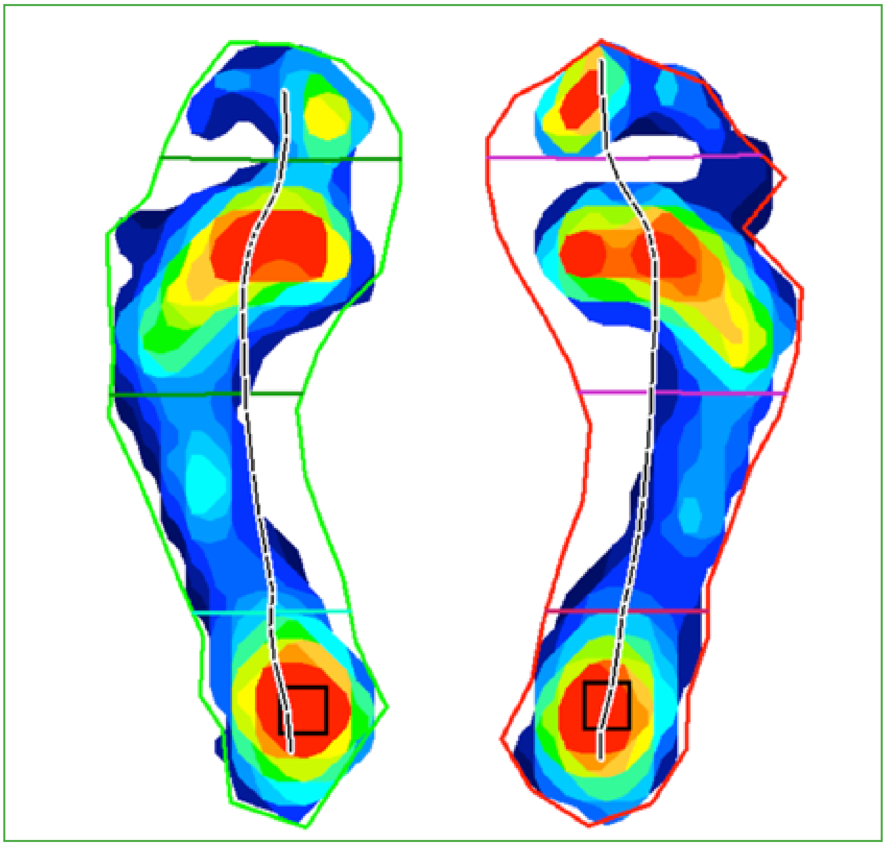

Figure 2. Result of a dynamic gait test with 5 steps for each foot. It is presented with the excursion index of the center of force and the division into three areas or boxes (heel, midfoot and forefoot).

Statistical Analysis

Descriptive statistics with the R program were used. Continuous numeric variables are expressed as mean (or average) and standard deviation.

RESULTS

316 records corresponding to both feet of 158 individuals were included, 105 (66.5%) were women. Age ranged from 18 to 82 years (mean 47.4, standard deviation [SD] 16.1). The body mass index of these patients ranged from 16.9 to 30.9 (mean 23.3; SD 2.9).

Fourteen variables corresponding to foot measurements in asymptomatic patients were analyzed. The mean and SD results of the measurement of both feet of each patient are reported. The results are shown in the Table.

Table. Functional foot results during the stance phase of gait measured with a force platform*

	Asymptomatic feet (n = 316)
	Mean (SD)
Full foot	
Contact time (seconds)	0.79 (0.09)
CPEI (%)	16.55 (7.14)
Heel	
Heel Contact Time (%)	63.25 (6.25)
Heel Maximum Force (%BW)	69.34 (8.46)
Heel Maximum Force (kg)	45.22 (9.70)
Heel CoF Time (%)	20.0 (4.49)
Midfoot	
Midfoot Contact Time (%)	66.73 (5.64)
Midfoot Maximum Force (%BW)	15.9 (8.17)
Midfoot Maximum Force (kg)	10.7 (6.7)
Midfoot CoF Time (%)	25.99 (5.57)
Forefoot	
Metatarsal Contact Time (%)	92.55 (3.71)
Metatarsal Maximum Force (%BW)	87.52 (9.56)
Metatarsal Maximum Force (kg)	57.03 (11.71)
Metatarsal CoF Time (%)	46.20 (5.97)

SD = Standard Deviation, CoF = Center of Force , CPEI = Center of Pressure Excursion Index, %BW = Percentage of Body Weight.
*Measurements were taken in the office and analyzed using a program that divides the foot into three regions (heel, midfoot, and forefoot).

DISCUSSION

The results represent functional measurements of the foot during gait taken in an outpatient clinic, with a simple and reproducible method, using a force platform and a valid and reliable program.[13]

In electromyographic analyses of the function of each muscle during the gait cycle, Anderson and Pandy observed that muscles and ligaments are the main contributors to support and propulsion, representing 50-95% of the reaction force to gravity, while joints and bones have between 20% and 50% of the passive transmission of force.[16]

In the study presented, the force of reaction to gravity was measured, trying to standardize our values with the moment of function of each muscle as described by Anderson et al. At initial heel contact, the stabilizing muscles are active (glutes, quadriceps, hamstrings, biceps femoris, hip adductors and abductors and the muscles in the anterior compartment: tibialis anterior, extensor hallucis longus and extensor digitorum longus); while, in the area of the forefoot, the propulsive and support muscles (soleus and gastrocnemius) intervene only until the moment the foot takes off from the ground. The midfoot would be a connection area between the heel and the forefoot, which we call a “suspension bridge”.

Next, the parameters of the force/time relationship during a gait cycle in the stance phase are interpreted with respect to the biomechanical functioning of the foot using the division into three regions (rearfoot, midfoot and forefoot).

Contact time

It allows to infer the speed of the step (it measures the time of support of the complete foot in seconds). Its value could vary depending on age, sex, body mass index and in pathological conditions.[17] However, in 2013, Hillstrom et al.[4] observed that, in asymptomatic patients, the contact time did not vary according to the different types of feet (flat, straight and cavus).

CPEI

It expresses the value of the path of force (CoF) that could help define foot types. Lower values are associated with greater pronation and higher values with supination and could also show variations according to age and contribute to the diagnosis of pathological conditions.[8,12] However, opinions are controversial, since some authors did not find the CPEI useful for defining foot types.[11]

Measurements according to the area of the foot

Heel

Heel Contact Time (% contact): percentage of the time that the heel is flat on the ground while the CoF moves towards the midfoot and forefoot. In this series, the value was 63.45% of the total contact time and it is a parameter that could detect difficulties in heel take-off in pathologies of the triceps surae, osteoarthritis of the knee, ankle or failures in the windlass mechanism. Its prolongation could be related to the collapse of the arch of the foot.[17-19]

Heel Maximum Force (%BW): Heel contact on the ground resembles the descent or landing of an aircraft on the runway. The initial contact is at low speed,[20] but the stabilizing muscles (hip and knee flexors and extensors, and foot dorsiflexors) intervene so that the force is not directed forward violently. The main stabilizers are the glutes, quadriceps, hamstrings and tibialis anterior muscles, as well as the extensor hallucis longus and the extensor digitorum longus. These muscles are already active in the flight phase of the foot, but their power cannot be captured with the force plate. The value is normalized in relation to body weight. In older adults, this value would be decreased by less muscular power that could be linked to a collapse of the internal arch, metatarsalgia, pathologies of the first ray, or loss of balance.[17.19]

Heel CoF Time (time in %): How fast is the force passing through the heel region? This will depend on the ability of the stabilizing muscles to smooth the landing of the foot on the ground and also the ability of the foot dorsiflexors so that the force does not go quickly to the midfoot and metatarsal region. Jameson et al. reported the results in children and the values of this series coincide with them;[7] however, there could be changes in this value when age is taken into account.

Midfoot

Midfoot Contact Time (% contact): percentage of time that the midfoot is in contact with the ground from the moment it lands until only the metatarsal is on the ground. In this sample, the value was 66.73%. If we try to make a comparison, the midfoot, which is anatomically related to the internal longitudinal arch and the transverse arch,[21] behaves like a suspension bridge, where the CoF advances if the structure is healthy. Any pathology that alters it will cause a CoF arrest and further increase the damage to the structure. It could be a parameter to evaluate progressive arch collapse, posterior tibial dysfunction, plantar ligament injury (snap ligament), plantar fasciosis, etc. It could also indicate a failure in the propulsion mechanism and takeoff of the foot from the ground (windlass).[22]

Midfoot Maximum Force (%BW): maximum force supported by the midfoot during the time of support in this area. If the structure is anatomically normal, the force can proceed to the forefoot; on the other hand, if the structure is not normal or is deteriorated, this force could cause the arch to collapse. The value is normalized with body weight.

Midfoot CoF Time (time in %): How fast does the force pass through the midfoot area? It will depend on the resistance of the anatomical structure of the medial longitudinal arch and the transverse arch of the foot, the power of the stabilizing muscles, the greater or lesser power of the soleus and gastrocnemius muscles, and the ability of the knee to be placed in full extension. so that the force can pass into the metatarsal region.[23] This is why the midfoot receives here the denomination of a "suspension bridge". As the years go by, would there be an increase in the time spent on midfoot force in an asymptomatic patient? What about the pathological processes that compromise the arch? Do the surgical procedures we perform modify these parameters?

Forefoot or metatarsal area

Metatarsal Contact Time (% contact): Metatarsal contact is associated with the descending or landing effect of the foot on the ground, similar to landing an airplane on the runway, where the metatarsal area is like the front wheel of the airplane. The time it takes the metatarsal to land will depend on the stabilizers (muscles and tendons) and the—healthy and flexible—joints (hips, knees and ankles). In this study, the value was 92.55% of the total stance phase for asymptomatic patients.

Metatarsal Maximum Force (%BW): the maximum force in the metatarsal area is related to the toe-off at the end of the stance phase and mainly involves the triceps surae muscle (soleus and gastrocnemius) providing support and propulsion.[17] The value is normalized with body weight. In older adults, there could be a reduction in force and, therefore, in propulsion, which could reduce speed and generate pathologies of the forefoot, such as hallux valgus, metatarsalgia, hammer toes, gait instability, and risk of falls.[24] However, Hessert et al. considered this situation as an adaptation to gain stability over the years.[25]

Metatarsal CoF Time (time in %): the time that the CoF remains in the metatarsal area is directly related to its function of support, propulsion and takeoff. Just as a hydraulic jack lifts a vehicle, the metatarsal resting on the ground prepares the takeoff by raising the heel and midfoot, while the propulsive force advances towards the first toe or hallux until the foot is completely lifted off the ground.

Heel, Midfoot and Metatarsal Maximum Force (kg): the absolute values of maximum force in the areas of the heel, midfoot and forefoot are exposed to great modifications due to differences in sex, weight, body mass index and are not normalized, which could generate biases when interpreting the statistical results.

Biomechanical functioning data were recorded without using ionizing radiation, with a short period of data collection and fundamentally, in the outpatient office of a foot and ankle specialist surgeon. This could allow us to obtain new functional parameters, and generate new hypotheses (potentially functioning as a control group, to be used in comparison to pathological cases).It would have been interesting to explore the variability of these findings considering age, sex, body mass index, and type of foot (flat, arched, or straight). However, this was not possible due to the limited number of cases included in the study. In 2013, Hillstrom et al.[4] observed that asymptomatic patients had some similar gait parameters, such as total contact time, regardless of foot type. For this reason, in this study, radiographic measurements, clinical foot morphotype, and characteristics such as stiffness or flexibility were not considered, only functional results. In future research, it would be interesting to compare these functional parameters with scores that take quality of life into account, especially in older people.

CONCLUSIONS

The functional parameters of the foot evaluated in asymptomatic patients were presented, mainly considering the contact time of the foot on the ground, the force in each region of the foot (heel, midfoot and forefoot) quantitatively, and the trajectory of the force. These measurements do not use ionizing radiation, can be performed in an outpatient office, and are simpler than a sophisticated biomechanics laboratory. The findings could be used as reference values to detect pathological gaits.

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