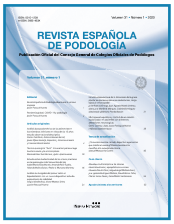

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Analysis of stiffness of the first ray during weightbearing with a new device: a feasibility exploratory study

Análisis de la rigidez del primer radio en bipedestación con un nuevo dispositivo: estudio exploratorio de viabilidad

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Keywords:

First ray, stiffness, first metatarsal, static, weightbearing, dorsiflexion, measurement, characterization, feasibility, elastic modulus.

Abstract

Introduction: The mobility of the first ray has generated controversy due to its subjective assessment during exploration of the foot. Historically, this assessment has been done manually for quantification of first ray dorsal excursion being these measurements somewhat subjective.

Patients and methods: The present study quantifies the stiffness or first ray dorsiflexion with a new device that measures the vertical displacement of the metatarsal head from 0 to 10 millimeters, in addition to the vertical force, measured in newtons.

Results: Thirty-nine feet of 22 asymptomatic were tested in the device. By pooling all data, a stiffness graph was created showing the behaviour of first ray stiffness. The graph showed a lineal behaviour which fitted with theoretical predictions from 0 to 5.3 mm of vertical displacement (44 newtons). From that point, the graph showed an erratic and nonlinear behaviour, probably because of foot adaptations of the patients during the test.

Conclusions: Although today there is no single device able of measuring the dorsiflexion resistance of the first ray during standing, the present study tries to perform an exploratory and feasibility analysis with a new device in non-pathological subjects. The study gives interesting data on first ray dorsiflexion stiffness behaviour that could be used in future studies.

Palabras clave:

Primer radio, rigidez, primer metatarsiano, estática, bipedestación, flexión dorsal, medición, caracterización, viabilidad, módulo de elasticidad.

Resumen

Introducción: La medición de la movilidad del primer radio ha generado controversia debido a su valoración subjetiva durante la exploración del pie. Esta ha sido históricamente realizada de forma manual y cuantifica la movilidad del primer radio en flexión dorsal, siendo esta medición un tanto subjetiva.

Pacientes y métodos: El presente estudio cuantifica la rigidez o resistencia a la dorsiflexión del primer radio con un nuevo dispositivo que mide el desplazamiento vertical de dicha estructura (de 0 a 10 mm), además de la fuerza en newtons, en bipedestación en 39 pies de 22 pacientes asintomáticos en sujetos sanos.

Resultados: Se estudiaron un total de 39 pies de 22 pacientes asintomáticos. Se creó una gráfica de rigidez en flexión dorsal para el primer radio, juntando todos los datos de la muestra. La gráfica ofrecía un comportamiento lineal muy similar a lo esperable teóricamente hasta 5.3 mm de desplazamiento vertical (44 newtons de fuerza). A partir de esta distancia el comportamiento fue más errático y no lineal, posiblemente debido a acomodaciones del pie de los pacientes durante el test.

Conclusiones: Aunque a día de hoy no existe un aparato capaz de medir la resistencia a la dorsiflexión del primer radio en bipedestación, el presente estudio trata de realizar un análisis exploratorio con un nuevo dispositivo para cuantificar dicha medición en sujetos no patológicos, aportando datos que pueden resultar interesantes para futuras investigaciones.

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INTRODUCTION

The mobility of the first ray has been historically determined with the Root et al's clinical test[1] (Figure 1), being one of the tests most used at the moment in foot biomechanical assessment. One of the problems associated with this clinical test lies in the inability to reliably measure the metatarsal displacement in dorsiflexion together with the force carried out to mobilize it, which can be very different from one patient to another and from one clinician to another. Several studies[2-4] have assessed the mobility of the first ray, although this has always been done under unloading conditions, manually or with devices that measure the dorsal displacement of the first ray. All of these explorations have been shown the assessment of first ray mobility to be unreliable, subjective, and furthermore do not quantify the degree or amount of force the first ray is subjected during the exploration.

The standard term commonly used in biomechanical literature to define the mechanical resistance of a body structure to a movement is stiffness[5]. This concept takes into account two factors: displacement and applied force. Related to the first ray, the concept of stiffness could be defined as the quotient between the amount of movement into dorsiflexion of the first ray and the force performed into dorsiflexion under the head of the first metatarsal. The combination of the magnitudes of movement together with the applied force allows a more precise description of the mechanical characteristics of the first ray than if we only relied on the movement without taking into account the exact amount of force[6].

Both, the increase and decrease in stiffness or resistance to dorsiflexion of the first ray of the foot, can lead to alterations that have been related to the development of several disorders such as hallux abductus valgus (HAV), functional hallux limitus (HLF), hallux rigidus (HR), lesser rays transfer metatarsalgia, increased subtalar pronation, stress fractures in the second and third metatarsals, sesamoiditis, increased subtalar supination, etc.[7-9]. However, so far there is no device that evaluates the stiffness of the first ray in a reliable and objective way, and this assessment is performed in the clinical world subjectively determined by the experience of the explorer. This aspect is especially important, since decisions based on both surgical treatments and conservative foot treatments are frequently made based on these observations. For all these reasons, the present study tries to quantify the mechanical behavior of the first ray using a new device that measures the resistance to dorsiflexion of the first ray during weight-bearing.

Figure 1. Clinical maneuver to determinate the movement of the first ray.

PATIENTS AND METHODS

This study is classified as a cross-sectional study (observational and descriptive). The study was approved by the ethical committee of the University of Valencia, with H1513760827611 number as part of a larger investigation whose sample includes the patients in this study.

Study population

To carry out this work, patients who attended to Sergio Miralles Podiatric Clinic (Castellón de la Plana, Spain) from 06/21/2018 to 06/27/2018 were studied. Patients with various reasons for consultation underwent an anamnesis and an exploration in search of some exclusion criteria that did not allow them to participate in this study.

Exclusion criteria were: patients under 20 years of age, to ensure that bone maturation had been completed, previous foot surgery history, presence of neurological conditions that decrease sensitivity in the foot (diabetes mellitus, peripheral neuropathies, etc.) or that affect the stability of the subject (Parkinson's disease, etc.), presence of flatfoot or cavus foot deformity diagnosed by clinical exploration, presence of first ray or first metatarsophalangeal joint disorders (HAV or HL / HR), ligamentous hypermobility and women who are pregnant or think they may be. All participants signed an informed consent to participate in the study prior to an explanation of the nature of the study and the test what was going to be done.

Instrumentation

The new device consists of a raised platform similar to a podoscope where both feet are supported, one of them with a

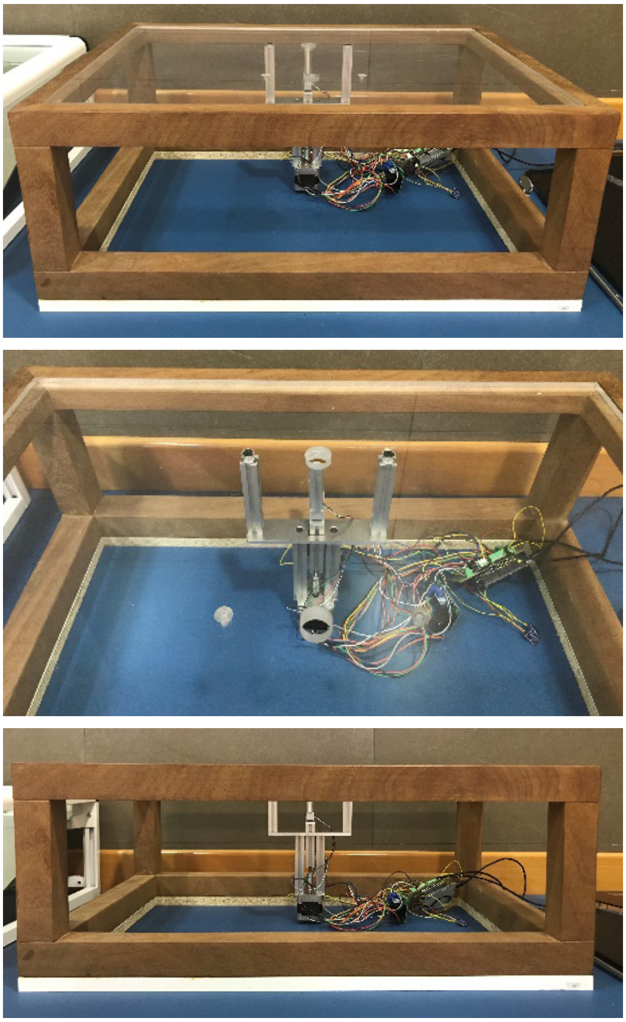

Figure 2. Measuring device.

hole under the head of the first metatarsal (Figure 2). Below the hole there is a device with a motor anchored to a central rod that rises vertically pushing the head of the first metatarsal. The central rod rises from -10mm (10 mm below the bearing surface) to 14 mm (14 mm above the bearing surface). Every 0.25 mm it stops 3 seconds and measures 20 times the force it receives, giving the average of those 20 measurements. In this way, the stiffness coefficient graph is obtained, where on the ordinate axis (Y axis) is displayed the force made by the rod and on the abscissa axis (X axis) its vertical displacement.

The device is made by a stepper motor, with the purpose of generating the vertical thrust force of the central rod that has a measuring device at its tip. The components are: a resistive load cell located in the central rod, a microcontroller as a management element of the measuring device, a microcontroller as a management element of the stepper motor, a microcontroller as a coordinating element of all the elements of the system and as a bridge between the device and the control software. This measuring device was built and tested by a mechanical engineer and a computer scientist who participated in the project.

Study protocol

Firstly, a brief anamnesis and foot exploration / inspection were carried out, which allowed to know whether the patient could be included in the study taking into account the exclusion criteria. Age, weight, height and foot number of all patients were recorded as anthropometric data of the sample, all of them reported by the patient himself. With a sitting or supine position of the patient, a mark was made exactly in the place where the rod was intended to impact by exerting its vertical thrust, coinciding with the head of the first metatarsal on its plantar surface of both feet.

Afterwards, the patient was placed with the help of the researcher on top of the new device in weightbearing position, with the head of the first metatarsal on the rod, using if necessary a tool - such as a small mirror - to verify that the rod coincides with the mark previously placed under the head of the first metatarsal. With his hands, the patient touched the wall, just for stability, without increasing the inclination with respect to the point of support of their feet, to decrease the typical oscillations of weight-bearing during the test, and he was asked not to modify the position of the foot.

After that, through specific software designed for the device, the explorer started the exploration (pressing the button "start") where the central rod begins to rise as previously explained from -10 mm (10 mm below the support surface) to 14 mm (14 mm above the bearing surface), stopping for 3 seconds every 0.25 mm of vertical displacement of the rod, obtaining during that pause 20 measurements of the force it receives and providing the final average of those 20 measurements. While it is true that all patients did not support the rise to 14mm above the ground level, so data up to 10 mm above the ground level were taken into account. This elevation was performed in all patients in the sample and the results obtained with this elevation were measured regardless of the dorsiflexion range of the first ray the patient had or the compensations done by each patient. Patient was asked to try not to change the position of the foot during the test (Figure 3; Video 1).

Statistical analysis

Statistical analysis was carried out by means of Microsoft Office program and its Excell application (2013 version). Data from each subject was collected in an Excel sheet in which the graphic with the coefficient of stiffness of each subject was obtained. Results were depicted graphically with the y-axis showing the force applied by the rod measured in newtons

Figure 3. Device during measurement with a subject on top.

and with the x-axis showing the linear displacement in millimeters also measured by the rod.

Afterwards, all data from all subjects of the study were pooled together to depict the mean stiffness graph of all subjects of the study. A 95% confidence interval was also calculated. Mean and standard deviation of anthropometric data of study population was estimated with SPSS program; version 21 (IBM; Arkmork, USA).

With the mean stiffness graph of all subjects of the study, a stiffness coefficient was calculated which represents the slope of the curve of the graph. For the estimation of that stiffness coefficient, it was stablished visually the zones of the graph that showed a linear behavior and zones with a nonlinear behavior or the graph were not used for the estimation of the stiffness coefficient. The coefficient was calculated as the quotient of the force (measured in newtons) divided by the displacement of the rod (measured in millimeters). Stiffness coefficient was expressed in newtons / millimeters (N/mm)

RESULTS

A total of 39 feet of 22 patients who agreed to collaborate in the study and who met the inclusion criteria were studied. Table I shows the anthropometric data of the patients of the present study.

Figure 4 shows the pooled stiffness graph of the first ray measured in the 39 feet of the study. This graph shows the relationship between force in newtons and displacement measured by the device in millimeters in 39 feet of 22 patients. The middle line shows the mean stiffness of all the study patients and top and bottom lines shows the 95% confidence interval.

Visually, two different parts of mechanical behavior of the first ray could be established with the device tested. The first part shows a behavior that could be considered linear of the stiffness of the first ray and goes from 0 mm to up to a little more than 5 mm of vertical displacement (5.4 mm). The second part ranges from 5.4 mm to 10 mm vertical offset. This second part shows a much more erratic behavior and that can hardly be classified as linear.

In the first part of the graph (from 0 to 5.25 mm of vertical displacement) 2 different segments can also be observed. Initially, the behavior is of rigidity increased progressively to the first 2 mm (20 newtons of force), subsequently continuing with a linear increase to 5.25 mm of vertical displacement (44 newtons of force). The calculated stiffness coefficient for the first segment (from 0 to 2 mm) was 5.45Nw / mm and the calculated stiffness coefficient for the second segment (from 2 to 5.25 mm) was 7.87Nw / mm.

In the second part, between the 5.25 mm and the 7 mm vertical displacement of the rod, it is appreciated that data does not follow a linear pattern like the first part of the graph, showing a smoother slope, that is, the greater the displacement of the rod, the force does not increase linearly, with some variant in negative which indicates a loss of stiffness of the first ray from the 5.3-5.5 mm displacement. At the same time, between 7 mm and 8.7 mm, proportional behavior is re-estimated for a shorter period with a less pronounced slope, but with a more linear behavior than the previous one. In the last

Table I. Anthropometric data of the study population.

Sex	Age (Years)	High (Cm)	Weigh (Kg)	Foot size	Nº feet R/I	% Of unilateral vs. Bilateral feet studied
Men 40 % (n = 9) Women 60 % (n = 13)	44.22 ± 16.48	167.81 ± 7.95	68.63 ± 14.10	40.59 ± 2.92	20 PD/19 PI	22.7 % unilateral (n = 5) 77.3 % bilateral (n = 17)

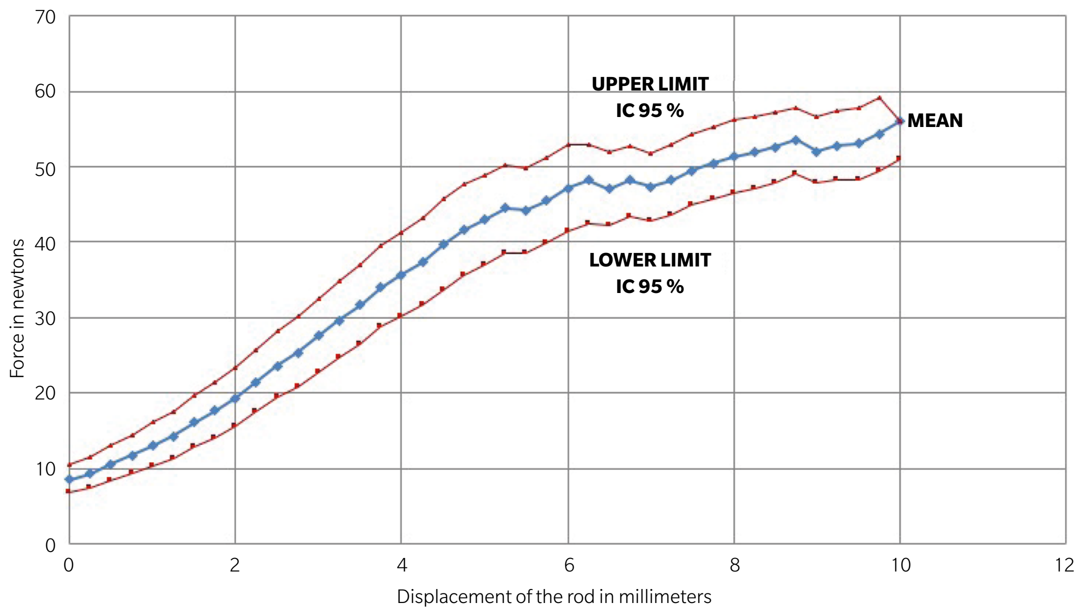

Figure 4. Stiffness graph of the first ray.

part, between 8.7 mm and 10 mm, certain negative values are contemplated followed by an analogous slope with respect to the third part of the graph. Due to the loss of general linear behavior in this second part of the graph, the stiffness coefficient could not be calculated in this segment of the graph.

DISCUSSION

Nowadays, there is no device capable of measuring the resistance to dorsiflexion of the first ray ("stiffness") during weight-bearing. The present study attempted to perform an exploratory analysis with a new device to characterize the stiffness of the first ray in a sample of non-pathological patients. The study was carried out in a very generalized way since the age of the participants is very diverse, so much that the range was between 20 and 71 years. It is also true that the anthropometric characteristics and the activities they carry out are very different. These aspects could directly or indirectly influence the resistance to dorsiflexion of the first ray, but they were not taken into account when conducting the investigation.

Theoretical descriptions[10,11] and previous cadaveric studies[12] on the behavior of the first ray predict a non-linear gradual increase at the beginning of the test (first 15-20%) when the soft structures begin to tighten in such a way that the first ray increases its stiffness exponentially. After this first initial stage, the prediction is a growth of linear stiffness behavior during the middle stage of the graph (elastic behavior) until, in the final stage, first ray increases exponentially its stiffness due to an increase in tension of the soft parts that maintain the stability of the first ray producing a very large increase in force with a few millimeters of vertical displacement. This occurs in the final stage whin the soft plantar structures that stabilize the first ray are in maximum tension.

Taking into account Picture 4, data obtained in the present study agree with the description in the first and second stage. In the first stage, there was a gradual increase in stiffness that corresponds to the linear displacement of the rod from 0 to 2 mm (stiffness coefficient of 5.45 N / mm) and which is equivalent to a force interval of 9 to 20 newtons over the first metatarsal head, followed by a linear increase in stiffness of the first ray that extends to approximately half the graph (5.25 mm vertical rod displacement equal to 44 newtons) and allows the stiffness coefficient of the first ray to be calculated during this stage, being 7.87 N / mm. From here on, the behavior of the stiffness measured in patients is more erratic and does not follow a linear behavior, producing a decrease in stiffness when the theoretical models predict an increase in stiffness from this moment on. This finding may be due to an error in the positioning of the patient's foot at the point where the rod of the device exerts vertical elevation or the modification of the foot position the subjects performed theseves in a subtle way (ex. supination of the foot or muscle contraction) in order to avoid an increase in the forces of the rod on the first metatarsal head that may begin to suffer a painful stimulus in that area. The opinion of the authors of the present study is that the subtle change in the position of the foot (semiconscious or unconscious in the face of a stimulus that begins to be painful under the first metatarsal head) is the main reason for the results in the final stage of the first ray stiffness graph found in this study. Despite patients were explained not to change the position of their foot during the test and the observer controlled that there were no changes in the position of the foot, small contractions in the foot musculature (ex.: posterior tibial, proper flexor of the Hallux ...) or oscillations in weight-bearing position could be responsible of this behavior.

Stiffness is a measure of the resistance to deformities that an elastic material suffers. In other words, the term "stiffness" describes the force necessary to carry out a certain deformation in a structure. Generally speaking, the definition of stiffness as[13]: "'Stiffness' = 'Load' divided by 'Deformation'" includes the concept of "Deformation" created by the amount of "Load" supported. There is an enormous number of possible configurations of the concept of "Load" acting on a structure (Force, Moment, Stress, Arbitrary groups of forces, etc.) linked to the concept of deformation of this structure that can be quantified (displacement, deformation, angle, ray, curvature, etc.). Therefore, the term "Stiffness" of a structure always requires an exact description of the load configuration and the exact type of deformity measured. In the present study, the calculated stiffness coefficient refers to the force in newtons measured by the rod on the first metatarsal head divided by the displacement in millimeters of the rod. This aspect is especially important when comparing the results of the present study with those of other studies. On the stiffness graph like the one made in this study, the calculated stiffness coefficient is equal to the slope of the straight line in the first half of the graph.

The stiffness coefficient calculated in this study is analogous to the modulus of elasticity or Young's modulus calculated for elastic materials. The modulus of elasticity is defined as the stress / strain quotient and is considered a fundamental characteristic of that material. The value of this elastic modulus is generally measured in Gigapascals or GPa and represents the stiffness of the material. The mechanical and structural characteristics of the human body can be observed in various organic materials. Thus, the elastic modulus for a tendon is 0.4 GPa, for the skin 0.5 GPa and for cortical bone it is 17 GPa[14]. The main difference with the stiffness coefficient calculated in the present study is that the concept of "load" calculated in Young's modulus refers to "tension" or "stress" of the material expressed as the force supported per unit surface area of the material, a value that could not be calculated in the present study, so the values obtained in the present study are not comparable with those of Young's modulus studied in other organic materials. At the same time, it is important to understand that the stiffness coefficient calculated in the present study refers to the stiffness of a functional set of bone segments joined by joints (first ray) and not of a single isolated material (bone, ligament, etc.). We understand that the value obtained in the present study is a first approximation to the stiffness coefficient of the first ray that must continue to be investigated in subsequent studies with a better defined and less heterogeneous sample.

The present study shows certain limitations that must be taken into account when interpreting data. The first limitation already mentioned is the heterogeneity of the sample in terms of age, sex and anthropometric data, which may influence the results obtained. This heterogeneity is also applicable to the position of the foot of the patients in the sample (in pronation or supination) which, being an exploratory feasibility study, was not taken into account in the exclusion criteria and could influence the values obtained from measurement of the stiffness of the first ray. On the other hand, the anatomical dimensions of this segment are not the same in all patients, but the rod is the same for all, for this reason there may be cases where the rod did not exert vertical elevation where it should. Likewise, it is true that the vertical thrust is not purely on the bone segment of the first ray since more plantar to this, there is soft tissue such as plantar fat, variable aspect among patients, and the glenosesamoid apparatus. This is an important aspect that should be considered in subsequent studies.

In conclusion, the present study provides data on a new device to measure the stiffness of the first ray under static load conditions. The data obtained showed agreement with the theoretical predictions up to a load of 44 newtons (5.25 mm vertical displacement). Based on these values, data showed a more erratic behavior that may not be reliable and that could be explained by accommodations in the position of the patient's foot in the presence of excessive load received on the first metatarsal. Although data is promising, the relevance of this study lies in knowing that this new device offers data that appear to be reliable for resistance to dorsiflexion of the first ray during weight-bearing up to 5.25 mm vertical displacement of the rod and not beyond it. Further subsequent studies are necessary to determine normality values, stiffness values in different groups with alterations in the foot (flat foot, cavus foot, HAV, mechanical metatarsalgia, etc.) and to determine the effect of first ray stiffness of different therapeutics such as surgical treatments, splints or insoles treatments and rehabilitation treatments.

CONFLICT OF INTERESTS

Authors do not have any conflict of interests regarding the present study.

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None.

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