The potential of ultrasonography in the evaluation of foot orthotics therapy

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Introduction

According to the tissue stress theory, “a foot orthosis is an in-shoe medical device which is designed to alter the magnitudes and temporal patterns of reaction forces acting on the plantar aspect of the foot in order to allow more normal foot and lower extremity function and to decrease pathologic loading forces on the structural components of the foot and lower extremity during weight bearing activities” [1]. The first goal of the conservative treatment of foot pathomechanics using foot orthotics is to decrease the internal pathological stress within foot tissues making possible their rehabilitation [2]. The first steps of the tissue stress theory, which are included in the diagnosis and prescription protocol, consist of identifying the tissue structure being excessively stressed and the responsible factors [2,3]. A convincing evidence of the efficacy of foot orthotics consists of the challenging outcomes which are translated in biomechanical parameters or patient outcomes reported measures (PROM) [4,5]. If the main objectives of orthotic therapy are to reduce the internal pathological stresses in the foot’s structure, then the outcomes used to demonstrate their efficacy should reflect this process. According to the literature, there are numerous difficulties to evaluate internal stresses in the foot structure, no specific technologies being yet feasible at a clinical level for this purpose [6], while a better understanding of the musculoskeletal injuries and their relationship with foot orthotic therapy is not possible in the absence of the predictive models [7]. Ultrasonography (US) is easily accessible as an imagistic technique and frequently used in clinical practice [8-10]. It is largely

Abstract

Foot orthotics prescription is based on the foot functioning paradigms with tissue stress theory being in avant-garde. The main goal of orthotic therapy is to reduce the internal tissue’s pathological stresses in the foot structures. Traditionally, ultrasound scanning technique depicts anatomic related data of both common and uncommon pathology encountered in the clinical practice, helping in diagnosing, treating and evaluating, which are equally important for the practitioners. Its accessibility, compared to biomechanical modelling, makes this technique a valuable tool in the field of foot and ankle disorders. Despite its user-dependent limitation, the ongoing technical progress improves the ability of ultrasonography as a highly advanced procedure in musculoskeletal imaging, being also a valuable searching tool for musculotendinous mechanics or morphological changes as a result of a conservative intervention. The aim of the present work was to perform a review of the state of the art concerning the usefulness of ultrasonography in the study of foot orthotic therapy and to analyze its effectiveness.

Keywords: foot orthoses; ultrasonography; mechanical phenomena; texture analysis; computer assisted diagnosis
used for the detection of abnormal echostructures and echogenicities in different tissues including the diabetic foot: muscles, osteo-tendinous structures, subcutaneous layer, and integument [11], which are consistent with the first step of tissue stress theory. Opposite to the limitations of the traditional complex motion analysis, US allows investigation of the muscle-tendon mechanics making possible an in-vivo indirect estimation of the forces acting on them. It may be based on ultrasonographic measurements of the tendon length changes combined with plantar flexion torques in isometric tests [12] or on the non-linear relationship between speed of ultrasound waves in a tendon and the applied traction force [13]. Quantitative ultrasound tissue characterization based on conventional real-time B-mode US has proved to be an objective tool for the assessment of the various tissue architectures [14-16]. Muscle-tendon’s architecture and mechanical properties are correlated with force generation [17], while structural changes of the tissues (tendons, fascia, soft tissue) investigated through imagistic techniques as a texture analysis or a “blob analysis” permit the evaluation of the morphological changes and the possible relationship between increased tissue stress and risk of injury [8,11,15]. Ultrasound tissue characterization (UTC) techniques allow quantifying the tendons structural changes, classifying tissue structures in 4 echotypes where the 1st and the 2nd are more homogeneous and organized structures, while the 3rd and the 4th are more disorganized and variable (fibrillary or amorphous) echo-structures [18-21]. The purpose of this review was to find how the US could be used in order to evaluate the efficacy of foot orthotics therapy in the conservative treatment of foot pathomechanics.

Ultrasonography used to evaluate the muscle-tendon’s architecture

The muscle-tendon’s architecture is consistent with the measurement of geometrical parameters as muscle length and thickness, fibre and fascicle length, pennation angle, physiological cross-sectional area, and myotendinous junction displacement [17,22]. In a randomised controlled trial based on 28 subjects with pes planus divided into two equal groups (one using only foot orthotics and the other using foot orthotics and foot exercise) Jung et al demonstrated that, in an eight week period of time, both groups show an increasing of the cross sectional area (CSA) of the abductor hallucis (AbdH) muscle and of the strength of flexor hallucis compared with the baseline situation [23]. This increase was greater in the foot orthoses combined with the foot exercise group when compared with foot orthoses only. The medical devices used in this study were a custom-made foot orthotics (made from 1/8 inch polypropylene), and an ultrasound system with a 7.5 MHz linear array ultrasound probe which was employed in AbdH muscle imaging. The results of the study provide evidence against the hypothesis that the muscular atrophy may be induced by wearing rigid foot orthotics. Jung et al have used ultrasound measurements of the displacement of the medial gastrocnemius’ (MG) myotendinous junction and video gait analysis of the rearfoot position in standing wall stretching exercises with and without a medial arch support [22]. The authors concluded that there is a potential for minimizing the stress in MG as a result of a controlled laboratory study with 30 subjects divided into two groups (15 with pes planus and 15 with normal feet classified depending on navicular drop and resting calcaneal stance values) [22]. In the case of subjects with pes planus this effect can be explained through an increased length of the gastrocnemius as a result of stretching exercises while the subtalar joint was maintained in the neutral position based on the use of the arch support [22]. Analyzing the effect of three types of shoes (neutral, motion control, and minimalist) on the plantar fascia and intrinsic muscle morphology in a cross-sectional study Zang X et al conclude that the motion control shoes had increased the thickness of both the proximal plantar fascia (PF) and abductor digiti minimi (AbdM) when compared with minimalist shoe effect in a group of 21 recreational runners [24]. In this study US was also used. No difference was registered between these types of shoes on CSA and thickness of abductor hallucis (AbdH), flexor digitorum brevis (FDB) and flexor hallucis brevis (FHB). The hypothesis of the association between tensile forces in the medial and lateral sides of the Achilles tendon and eversion-inversion movement of the rearfoot was tested by Nester C et al, through the automated tracking of the ultrasound images of two regions of interest defined based on the distance between two reference points identified on each side (medial and lateral) of the tendon in 17 healthy subjects [25]. Based on this research, the authors concluded that altering the rearfoot motion with conservative interventions (taping, foot orthoses, and footwear) has a potential influence upon stress distribution in the Achilles tendon [25]. Farris et al had estimated the effect of two orthotic heel lifts having 12 and 18 mm heights respectively, on an Achilles tendon force during running in the case of 10 healthy females [26]. Using real-time B-mode US in conjunction with inverse dynamics method the authors had calculated the Achilles tendon’s force, instantaneous moment arm around the ankle joint center, and tendon’s length, demonstrating a reduction of the Achilles tendon force with both orthotic heel lifts compared with no heel
lifts baseline situation. According to the protocol the trials were performed barefoot while the heel lifts were directly attached under the subject’s heel using a 3M™ Transpore™ solvent-free adhesive tape.

**Ultrasonography used to evaluate the tissue’s structural changes and mechanical properties**

These features were analyzed in a quantitative manner through the measurement of the structural arrangement [18-21], tissue composition [15], mechanical properties (such as stiffness) [8], and detection of latent inflammation [11]. “Full capacity” of a tissue was defined as the ability to perform its normal activity without becoming symptomatic or injured [27]. Increased tissue’ stiffness (plantar soft tissues or fascial structure) carries the risk of injury (i.e. ulceration, heel pain or plantar fasciitis) [27-29]. US indentation methods were used for evaluating the mechanical properties of the plantar soft tissue (thickness, stiffness), providing useful information regarding mechanical behavior under vertical loading and an indication for the selection of the properties of the orthotic devices materials [30-32]. The influence of tissue’s properties (as bulk modulus and density) on the speed of the axial transmission of ultrasound waves [33,34] was used for the study of the human Achilles’ tendon tension as an effect of wearing footwear and orthotic heel lifts [34,35]. This work was based on the correlation established between the speed of the propagation of ultrasound waves and the load applied on the tendon which was investigated through a custom-made ultrasound device placed on the subject’s right Achilles tendon in the case of 12 active men recreationally walking on a treadmill. A direct relationship between the decreasing velocity of ultrasound and the decrease of tendon loading was established. The results of those studies are quite interesting as the sport footwear with a 10 mm heel height is usually recommended for the treatment of Achilles tendinopathy. This sport footwear has increased the tensile load in the tendon. A reduced tensile Achilles load was obtained by adding 12 mm height ethylene-vinyl acetate heel lift (41.00±1.00 Shore hardness) within the same shoes. The same method was able to differentiate the loading patterns between barefoot walking and slow running on a treadmill; the latter producing a higher and earlier peak in loading of the Achilles tendon compared with the former [33]. Based on US, Sweeney D et al measured the effect of foot orthotics geometry alterations (intrinsic and extrinsic medial wedges’ parameters in the case of 27 subjects, and the arch profile height in the case of 25 subjects) on the plantar soft tissue thickness in the area of the medial arch height as identified through the navicular position [36]. All subjects had a normal foot as defined through Foot Posture Index. The orthosis reaction forces and moments are driving the rotational equilibrium around foot joint axis [2]. According to Sweeney D et al, different foot orthotics’ prescription variables alterations will produce different compression effects on the plantar foot tissue, influencing the way in which ground reaction forces are transmitted back to the foot structure [36]. Based on ultrasound measurements of the soft tissue thickness under the second and the third metatarsal head, in three weight bearing conditions compared to the barefoot condition, Ibrahim M et al suggested the existence of a link between the decreasing of the plantar soft tissue strain and a decreasing of the plantar pressure in the case of three healthy subjects using three different types of pre-fabricates and custom-made silicon insoles [37]. Telfer S et al noticed the effect of both a flat orthotic heel and a contoured heel cup insert on the dynamic behaviour of the heel pad of 16 healthy participants walking on a treadmill at 1.25 m/s, using an orthotic embedded ultrasound transducer combined with a plantar pressure measurement [38]. The dynamic behaviour of the heel pad was evaluated through stiffness expressed as secant modulus (ratio of peak contact pressure and peak strain measured in the central area of the central heel pad) and energy dissipation ratio (ratio between area under loading curve and area under unloading curve on the pressure-strain graph). The statistically significant differences between the values of secant modulus between the flat heel insert (higher values) and contoured heel cup (lower values) conditions was considered as evidence for a decrease in the loading and deformation of the heel pad in the analyzed area.

The reliability of different ultrasound based measurements was reported in the literature: intra and inter-rater reliability of dynamic compression of the heel pad [38]; dorso-plantar thickness, medio-lateral width and CSA of AbdH [39], thickness and CSA of FHB, FDB, flexor hallucis longus (FHL), quadratus plantae (QP), AbdM, quadratus plantae (PER); thickness of tibialis anterior (TA) and PF [9,28]; fascicle length and pennation angle of MG and TA [40], hypoechoic rims around tendons, joint spaces, erosions, cartilage thickness [10]. However, ultrasonography remains a highly operator-dependent technique [9]. Seen from the perspective of tissue stress theory, there are not at this moment a large number of articles which have used ultrasound methods for evaluating the effectiveness of foot orthotics. Eight articles out of twelve identified in this section have been published between 2014-2016 and could represent an ascending trend in this regard.
Other US techniques with potential in the study of foot orthotics effectiveness

The reviewed articles from the previous sections of this work demonstrate the interest in using US in the study of foot orthotic therapy outcomes. Musculoskeletal ultrasound methods play an important role in the diagnosis and the scoring and monitoring of some pathological conditions of different anatomical layers [10,41]. These techniques, successfully applied in other clinical fields, have a great potential to be used in the study of foot orthotics effectiveness. In this regard, some achievements are worth being mentioned.

The homogeneity of the plantar soft tissues of the diabetic ulcerated foot is different from that of the non-ulcerated foot as is shown by the conclusion of a study by Naemi R et al, who investigated the deformability of the heel pad in the case of 5 diabetic neuropathic patients with unilateral foot ulceration using strain elastography [42]. The tissue’s homogeneity was expressed through stiffness gradients calculated between neighbouring pixels using the central difference method, on the horizontal, vertical and oblique directions relative to the image of the region of interest. Defining the tissue homogeneity, then its mechanical properties (stiffness) and its influence on stress distribution could be determined; it would be possible, in consequence, to study the influence of a medical device (foot orthotics) on the tissue “capacity” to react against external and internal forces that act on it. Energy responses output parameters have been calculated based on the texture analysis of a plantar soft tissue of a control group of 8 healthy subjects and a 16 diabetic subjects’ group (three of them having healed ulcers). It was possible to differentiate between the normal and diabetic foot and also between their non-ulcerated and ulcer prone areas. The association with soft tissue hardness has been substantiated by measurements within various plantar areas [8]. First, the authors applied the two-dimensional discrete wavelet transform on the region of interest, obtaining as a result four sub-images, having half of the spatial resolution of the original image, as follows: the first sub-image, denoted by $A^1$, was a low frequency component, corresponding to a low-low filter combination in horizontal and vertical directions, respectively; the second sub-image, denoted by $H^1$, corresponded to a low-high filter combination (low frequency filter in horizontal direction and high frequency filter in vertical direction) and highlighted the horizontal edges; the third image, denoted by $V^1$, corresponded to a high-low filter combination and emphasized the vertical edges. Finally, the fourth sub-image, denoted by $D^1$, highlighted the diagonal edges, being the result of a high-high filter combination. Then the energy was computed on each of the four resulted components, as being the sum of the squares of the image intensity values. The energy parameter was able to reveal significant differences between the tissue regions of diabetic and non-diabetic subjects, as indicated by statistical tests such as Welch Anova and Dunnett t-test. The same parameter, computed on the $A^1$ and $H^1$ components, emphasized significant differences between ulcered and non-ulcered regions. The energy was also found to be highly correlated (84% or above) with the externally measurable hardness of the plantar tissue measured in the ulcer prone areas [8]. These parameters are considered to mirror the structural changes taking place inside the tissue; as a consequence, the increasing of the tissue stiffness may affect its loading behaviour. In the frame of the research studies which are demonstrating the high levels of internal stress within the plantar soft tissue of diabetic foot compared with those from nearby foot-supporting interface and also the difficulties encountered in the clinical practice to evaluate the tissue’s internal stress [6], the computerized texture analysis of the ultrasound images of the injured or at risk tissues seems to be a promising source of significant information regarding the efficacy of foot orthoses.

Powerful texture-analysis methods such as the autocorrelation index, respectively the gray level co-occurrence matrix of second and superior order, or generalized co-occurrence matrices involving other features (such as edge orientations or textural microstructures) [43,44] as well as on multiresolution methods, such as the wavelet and Gabor transforms [8,45,46], could emphasize the properties of the tissue of interest – coarseness, homogeneity, roughness, structural complexity, or reveal subtle characteristics, leading to a further increase in accuracy concerning the differentiation between various tissue classes. Thus, the generalized co-occurrence matrices, of the second and superior order, based on gray levels, edge orientations, or textural microstructures obtained after the application of the Laws’ texture energy transforms [43,44], have, through the Haralick features, the ability to characterize, in a refined manner, the complexity of the tissue structure.

Then, specific methods for feature selection can be applied, in order to derive the set of relevant textural features. Defining an imagistic textural model of the tissue of interest, consisting of the complete and non-redundant set of the relevant textural features and of their class-specific characteristics (arithmetic mean, standard deviation, and probability distribution), represents an important step towards a reliable computer-assisted diagnosis. Powerful classification methods such as the Support Vector Machines, methods based on Decision Trees, on Artificial
Neural Networks, or classifier combination techniques [45] can be used both to validate the imagistic textural model and to perform automatic diagnosis.

Characterization of the tissue composition in muscles through computerized texture analysis using first-order and higher-order gray-scale features permits the evaluation of the content of non-contractile components and structure of supraspinatus and vastus lateralis muscles in healthy subjects [15]. Here, first order gray-scale features such as the mean, variance, median, histogram skewness and kurtosis were employed, while the higher order features were computed after the image thresholding and referred to the number and size distribution of the blobs in the image. A blob was defined as a connected region of at least three pixels having the value 1 (foreground pixels). The features regarding the latter class also provided information concerning the coarseness of the muscular tissue. The mean grey-scale intensity, as well as the number of spatially connected and homogeneous regions (blobs) indicated significant differences between the vastus supraspinatus and the lateralus muscle, as revealed the statistical tests (p<0.05). As the morphological changes and distribution of contractile and non-contractile tissue could be identified in different conditions such as training, ageing, pathological conditions it can be supposed that this method is useful in featuring how the tissue structure is modified as a result of foot orthotic therapy. Thus, once again, the computerized image analysis and the texture-based methods proved their significance in this research context.

The morphometry of the muscle’s tendons is related with the rearfoot motion in sagittal and frontal planes being associated with foot type (defined through some indices as Foot Posture Index, Arch Index, and normalised navicular height) [47]. It could be hypothesized that changing the rotational equilibrium or muscle imbalance through foot orthotics therapy, a potential influence on the foot tendon’s size [22,23] may arise; this may be linked with the tendon’s loading and modified activity related to compensatory movements [48]. Modelling the force production in striated (skeletal) muscle embraces different specific parameters related to the muscle’s architecture (physiological cross-sectional area, volume, fibre pennation angle and length) and physical and mechanical properties of the tissue (density, elasticity). Collectively, these should be considered when surgical or conservative treatment events are necessary [9,49-51].

Ultrasound indentation methods are useful for the investigation of the relation between the vertical force applied on the soft tissue and its shear modulus through elastography [52]. The shear forces are one of the main risk factors in diabetic foot ulcer development. Clinical evaluations of diabetic foot is less accessible, the technical difficulties are encountered in the design of a measuring device suitable for this purpose [53]. The evaluation of the shear modulus based on ultrasound methods has the potential to become a valuable alternative method.

Conclusions

Main ultrasound measurements associated with tissue loading and identified to be involved in the study of the effectiveness of foot orthotic therapy are: CSA, thickness, strain, length, moment arm, soft tissue compression, stiffness, energy dissipation area, and displacement of the myotendinous junction. Other complex ultrasound measurements are those resulted from texture analysis, tissue composition, muscle’s pennation angle, detection of latent inflammation. Those measurements have the potential to produce evidence of the modifying internal pathological tissue stress as a result of implementing foot orthotic therapy. Standard or custom-built ultrasonic devices are employed in the measurements.

US is a promising tool for the clinical evaluation of the effectiveness of foot orthotics. In combination with advanced texture analysis and with pattern recognition methods, it could lead to a highly accurate, powerful technique for computer assisted and automatic diagnosis, which is also non-invasive, safe, and inexpensive.

Conflict of interest: none

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