

3D characterisation of the dynamics of foot joints of adults during walking. Gait pattern identification

Authors:

E. Sanchis-Sales

Department de Podologia, Universitat de València, València, Spain

J.L. Sancho-Bru

Department d'Enginyeria Mecànica i Construcció, Universitat Jaume I, Castelló, Spain

A. Roda-Sales

Department d'Enginyeria Mecànica i Construcció, Universitat Jaume I, Castelló, Spain

J. Pascual-Huerta

Clínica del Pie el Cano, Barakaldo, Spain

Corresponding author:

E. Sanchis-Sales

ensansa@uv.es

Departament de Podologia, Universitat de València

C/ Jaume Roig, s/n

Valencia 46010

Spain.

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A detailed description of the kinematics and kinetics of the ankle, midtarsal and metatarsophalangeal joints of the feet of a healthy adult male population during barefoot walking is provided. Plots of the angles and moments in each plane during the stance phase are reported, along with the mean and SD values of 87 different parameters that characterise the 3D dynamics of the foot joints. These parameters were used to check for similarities between subjects through a hierarchical analysis that allowed three different gait patterns to be identified, most of the differences corresponding to the frontal and transverse planes.

Keywords: kinematics; kinetics; dynamics; foot joints; gait patterns

Introduction

There has been an increased interest in studying the biomechanics of the foot joints in recent years (Leardini et al. 2007; Bruening et al. 2012a). The study of the kinetics of the foot has been emphasised as an important tool for identifying, assessing and treating foot disorders (Bruening et al. 2012a; Dixon et al. 2012). The main motion of the foot is provided by the ankle, midtarsal (MT) and metatarsophalangeal (MP) joints, which play a relevant role during the stance phase of gait, especially for the adaptation of foot to the terrain and for the propulsion XXRefXX. Several works in the literature have studied the kinetics of the ankle joint under specific pathologies or after having been treated (e.g. Queen et al. 2012; Singer et al. 2013; Queen et al. 2014) by using models with the foot considered as a unique segment. But there are very few works reporting kinetic data of other foot joints, as this requires the use of a multi-segment foot model. It is also remarkable that one-segment foot models have been shown to overestimate ankle power during gait when compared with multi-segment models (MacWilliams et al. 2003; Dixon et al. 2012). A multi-segment approach is recommended to study the ankle and

midfoot kinetics, especially when surgical decision-making is based on the results of three-dimensional gait analysis (Dixon et al. 2012). Bruening et al. (2012b) used a three-segment model to calculate kinetic joint data from 17 children, describing maximal moment values in each plane, and observing the highest values for the sagittal plane. MacWilliams et al. (2003) reported kinetic data from 18 healthy adolescent subjects using a nine-segment model, providing plots with mean values and 95% CI for the joint angles, moments and powers during adolescent gait, and Rouhani et al. (2014) compared the kinetics of 10 healthy elderly subjects with those of 12 patients with ankle osteoarthritis, based on a three-segment model.

Most works in the literature dealing with the kinematics or kinetics of the foot joints focus on comparing pathological versus healthy populations. However the samples used for such analyses are quite small, thus making it difficult to reach definitive conclusions. This is especially true for the case of healthy adult male populations, as all works that have studied the kinetics of foot joints (other than the ankle) have focused on children or elderly people. Moreover, the largest sample considered for the kinematic analysis is that used in the work by Hunt et al. (2001), with 18 male subjects with ages ranging from 18 to 38 years. The kinematics of foot joints from 100 subjects were presented in the work by Nester et al. (2014), but these data basically represented the kinematics of females, as the sample consisted of 79 women and 21 men.

In addition, the data presented in many of the works in the literature are limited, providing only values for the specific parameters used for the comparisons (peak angle or moment, contact angle, etc.). Furthermore, these data present high dispersion values, which could be partially explained by the small size of the samples and a poor control of the subject's characteristics, e.g. the foot posture index (FPI) (Redmond et al. 2006),

but also because subjects might be using different gait patterns (Lin et al. 2011). A previous work identified two different normal gait patterns in the sagittal plane through a cluster analysis of the joint angles and moments at the knee and ankle joints (Simonsen & Alkjær 2012). No previous work has performed a similar cluster analysis on the angles and moments in the foot joints.

It is the aim of this work to provide a detailed description of the kinematics and kinetics of the ankle, midtarsal (MT) and metatarsophalangeal (MP) joints of the feet of a healthy adult male population during barefoot walking, while also investigating the use of different common gait patterns by normal subjects. These data could be clinically relevant for identifying abnormal foot dynamics, which has been shown to affect lower limb function (Powers 2003).

Material and methods

The experiment was approved by the University Ethical Committee, in accordance with the Declaration of the World Medical Association. Thirty adult male subjects (age 27.13 ± 3.82 years, weight 78.18 ± 13.90 kg, height 1.78 ± 0.06 cm) participated in the experiment. All the participants, free of lower limb lesions or pathologies, were properly informed and gave their written consent. The age of the subjects was intentionally low to avoid kinematic alterations due to joint degeneration caused by the process of ageing, and all them were checked to ensure they had a normal foot type, as classified by their FPI (Redmond et al. 2006), and very similar in both feet (right: mean 10.65, SD 0.67; left: mean 10.45, SD 0.76). All the participants except one reported to be right-foot dominant.

Each subject was asked to walk barefoot at a self-selected speed along a 7 m walkway. Before data collection, subjects were trained by having them walk on the walkway several times. The subject looked straight ahead while walking in order to

avoid platform targeting, and he had to step with his right foot on a pressure platform located in the middle of the walkway. The activity was repeated as many times as were needed to have five valid trials, discarding those where the subject did not step on the platform with his right foot.

The kinematics of the ankle (combined talocrural and subtalar joints), MT and MP joints of the right foot were recorded using an adaptation of the model proposed by Bruening et al. (2012a). The original model considered six degrees of freedom (DoFs) at the ankle and MT joints, but only flexion and abduction at the MP joint. Here, an additional marker was added on the medial side of the MP joint, in order to also consider six DoFs at this joint (Figure 1). Thus, a total of 20 reflective markers were tracked by an 8 infrared camera motion analysis system (Vicon® Motion Systems Ltd., Oxford, UK) operating at a sampling rate of 100 Hz. The 3D coordinates of the markers at each instant were used to obtain segment position and orientation (Söderkvist & Wedin 1993). Finally, joint angles were calculated at each instant from the upright standing static reference posture, which was recorded for each subject at the beginning of the experiment. The joint angles were obtained using a Cardan rotation sequence between distal and proximal segments (Grood & Suntay 1983): 1 - dorsiflexion/plantarflexion (DF/PF), 2 - abduction/adduction (AB/AD), 3 - inversion/eversion (IN/EV) (Figure 1). All kinematic data were low-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 10 Hz.

---- Insert Figure 1 here ----

To obtain the joint moments at the ankle, MT and MP joints of the right foot, the contact pressure distribution was used, along with the location of the joint centres obtained from the Bruening model. The contact pressure was recorded at a 100 Hz sampling rate with a 0.40 m x 0.40 m Podoprint® pressure platform (Namrol Group,

Barcelona, Spain), which was synchronised with the infrared camera system for compatibility with 3D kinematic data. The compatibility required also the spatial mapping of the location of the pressure cells to the global coordinate system used with the infrared cameras. This was accomplished by properly setting the global coordinate system during the calibration: the calibration wand was placed on the pressure platform, so that the origin of the coordinate system matched the centre of the pressure platform, and was aligned so that the X-axis and Y-axis corresponded to the mediolateral and anteroposterior axes, respectively. Then, the pressure data at each time were segmented by comparing the Y-coordinates of the contact cells at this time and those of the ankle, MT and MP joint centres for the time when the foot was fully contacting on the platform (E.g., cells with Y-coordinate between those of MT and MP joint centres were assigned to the forefoot segment). Then, at each segment, the total normal ground reaction force was calculated, along with the corresponding centre of pressure (CoP). The 3D joint moments were calculated as the cross product of the ground reaction forces on distal segments and the 3D distances between the CoPs and the joint centres, thus neglecting the effect of the weight of the foot, as well as the effect of foot angular velocity and linear and angular accelerations (Davis & DeLuca 1996; Crenna & Frigo 2011; Shamaei et al. 2013). Joint moments were expressed relative to the orientation of the local frame of the proximal segment. All joint moment data were low-pass filtered using a 4th order Butterworth filter with a cut-off frequency of 50 Hz, and, consistently with previous publications (Davis & DeLuca 1996; Crenna & Frigo 2011; Shamaei et al. 2013), the amplitudes were normalised to body-weight.

To analyse the dynamics of the foot joints during gait for each subject, the DF/PF, AB/AD and IN/EV joint angles and moments from each trial at each joint were

presented as a function of time, expressed as the percentage of the stance phase during the gait cycle.

In order to investigate the foot dynamics of the healthy adult population, mean values of the joint angles and moments across subjects and trials were computed and plotted versus time, along with the 95% confidence interval (CI). Local maxima and minima together with the (non-null) initial and final points from these plots were extracted as representatives of the global profile of the joint angle and moment curves in each plane, and were used as descriptive parameters of the dynamics of the foot joints. The ranges were also considered in order to allow comparison with other works. These descriptive parameters were computed for each subject for each of the five trials, and the Median Absolute Deviation (MAD) method was used to detect outliers (Huber & Ronchetti 2009; Rousseeuw & Croux 2012). The cut-off value selected was 5, so that when the absolute difference between one of the trials and the median of all the trials was bigger than five times the MAD of all the trials, the value was considered an outlier and was substituted by the mean of the other trials. After removing outliers, the mean values of the descriptive parameters across trials were used as representative of each subject, and the mean and standard deviation (SD) of these values across subjects were obtained as representative of the healthy adult population.

A more detailed analysis was performed to study the variation arising from subject particularities. The goal was to identify different gait patterns in the healthy adult population. Thus, a hierarchical clustering analysis was performed on the descriptive parameters obtained for the subjects. As a measure of dissimilarity between groups, the Euclidean distance was considered. And Ward's method was used for clustering, which minimises the total within-cluster variance, thereby maximising the homogeneity within groups.

To analyse the differences in the gait patterns identified, mean joint angles and moments across subjects and trials of each resulting group from the clustering analysis were obtained in the DF/PF, AB/AD, and IN/EV planes at each joint. These mean values along with the 95% CI were plotted as a function of time for each group.

For a better understanding of which parameters were the ones most affected by the gait pattern, a set of analyses of variance (ANOVAs) were performed with the parameters as dependent variables, and with the gait pattern as the factor. The mean and SD values across subjects of the parameters that were significantly affected were obtained for each gait pattern.

Finally, a linear discriminant analysis was performed, aimed at locating a reduced set of predictive parameters for classifying the subjects into the different gait patterns previously identified, for an easy classification of new subjects. The parameters that were significantly affected by the gait pattern were considered as independent variables, and the gait pattern as the grouping variable. The stepwise method was used, in order to enter the predictors sequentially. This method searches for the highest correlated predictors. In particular, the Wilks' lambda was used, which tests how well each independent variable (potential predictor) contributes to the model: 0 means total discrimination, and 1 means no discrimination. Each independent variable is tested by putting it into the model and then taking it out, generating a Λ statistic. The significance of the change in Λ is measured with an F-test. The variable is entered into the model if the significance level of its F value is less than the entry value (0.05), and is removed if the significance level is greater than the removal value (0.1).

Results

Foot dynamics of the healthy adult population during normal walking is described through the plots of the averaged DF/PF, AB/AD and IN/EV joint angles and moments

versus time shown in Figures 2 and 3. A detailed description of these figures is presented in Appendix A. The highest range of motion is in the sagittal plane, about 20° for both the ankle and MP joints, while it is significantly lower at the MT joint (13°). AB/AD and IN/EV ranges of motion are similar for all joints (between 8°-10°), except IN/EV of the MT joint, which is smaller than 5°. The ground reaction forces also generate the highest moments in the sagittal plane (up to 1.2 N·m/kg DF moments), followed by the frontal plane (up to 0.2 N·m/kg EV moments), with the MP joint being significantly less demanded than the ankle and MT joints. Moments in the transverse plane are very small, especially for the ankle and MP joints.

---- Insert Figures 2 and 3 here ----

A total of 87 parameters were used to describe the plots from Figures 2 and 3, thus characterising the 3D dynamics of the foot joints. The list of selected parameters is presented in Tables 1 and 2, along with the mean and SD values across subjects as representative of the healthy adult male population with normal FPI.

---- Insert Tables 1 and 2 here ----

Similarity between subjects with respect to these descriptive parameters can be observed in the dendrogram in Figure 4. A cut at the re-scaled Euclidean distance of 20 allowed three clearly differentiated groups (patterns of healthy adult population) to be identified. Pattern 1 was the largest one, with 17 subjects (2, 5, 7, 10, 11, 13, 14, 15, 16, 19, 20, 23, 24, 26, 28, 29 and 30), followed by pattern 3 with 10 subjects (1, 3, 4, 9, 12, 17, 18, 21, 22 and 25), and the smallest one was pattern 2, consisting of just 3 subjects (6, 8 and 27).

---- Insert Figure 4 here ----

From the total of 87 descriptive parameters considered, only 25 of them were found to be significantly affected by the gait patterns ($p < 0.05$) in the ANOVAs performed. Tables 3 and 4 show a list of them, along with the mean and SD values of each gait pattern across subjects. Plots of the mean joint angles and moments of each pattern across subjects are shown in Appendix B, and differences between patterns are carefully described.

---- Insert Tables 3 and 4 here ----

Finally, the linear discriminant analysis performed made it possible to identify a set of five predictive parameters for classifying the subjects into the three gait patterns, namely, time of peak AD moment at ankle (v_1), range of AB moments at ankle (v_2), peak AD moment at MT joint (v_3), time of peak DF angle at MP joint (v_4), and range of AB angles at MP joint (v_5). The discriminant scores found were able to predict the proper assignment of all subjects participating in the experiment to their corresponding patterns. The values of the predictive parameters can be used to calculate these two discriminant scores F_1 and F_2 for each subject, according to Equations (1) and (2), so that in the case that F_1 is positive, the subject belongs to pattern 1; if F_1 is negative and F_2 is positive, the subject corresponds to pattern 2; and if F_1 and F_2 are both negative, the subject is associated to pattern 3:

$$F_1 = 0.071v_1 + 4.684v_2 - 0.923v_3 + 0.459v_4 - 0.274v_5 - 46.779 \quad (1)$$

$$F_2 = -0.026v_1 + 26.39v_2 + 20.792v_3 + 0.436v_4 - 0.032v_5 - 40.063 \quad (2)$$

Discussion

This work provides detailed data describing the dynamics (kinematics and kinetics) of the ankle, MT and MP joints of the feet of a healthy adult male population with normal

FPI during barefoot walking. Before going into details, it is important to note that all joint angles reported were calculated from the upright standing static reference posture, with the subjects in the resting calcaneal stance position.

The profiles of the kinematic and kinetic curves obtained in this work are similar to those reported in previous works (Hunt et al. 2001; MacWilliams et al. 2003; Bruening et al. 2012a; Nester et al. 2014; Rouhani et al. 2014; Saraswat et al. 2014; Buldt et al. 2015). Some offset is observed in the kinematic curves of some studies (e.g. Saraswat et al. 2014), probably due to the use of different reference postures, which are not described in many of the works. Moreover, discrepancy in the values sometimes arises because of the differences in the characteristics of the subjects, e.g. age, sex, FPI or pathology. In this regard, a higher range of motion was reported by Nester et al. (2014) in the sagittal plane at the MP joint (45° vs 32°), which may arise from a greater laxity of the plantar fascia in female subjects. Although no significant differences in gait kinematics have been found with gender in the literature (Cho et al. 2004; Chiu & Wang 2007), the high dispersion of the kinematic values in these works might have hindered this effect.

The data presented in this study are more complete than those reported in previous works, with a detailed list of descriptive parameters that allow the behaviour of the foot joints to be described during the different stance phases. Furthermore, the SD values obtained here are smaller than those reported in other works (Hunt & Smith 2004; Rouhani et al. 2012), because of the careful selection of the subjects participating in the experiment. These data are clinically relevant: on the one hand, they can be used in future works to identify abnormal foot dynamics of different population groups; and on the other hand, they can serve as an aid in decision-making in surgical interventions

such as arthrodesis, for prosthesis design or as input to perform biomechanical analyses for different purposes.

The profiles of the kinematic and kinetic curves of the ankle and MT joints are quite similar, which means that both joints are functionally similar, in contrast to the MP joint. In this sense, the triceps surae has to counteract the dorsiflexor moments at the ankle arising from the ground reaction forces in an analogous way to what the plantar fascia does in the MT joint. This supports the existence of a mechanical relationship between the gastrocnemius-soleus complex and plantar fascia, also known as the Achilles-calcaneus-plantar system (Kirby 2002; Kirby 2008; Maceira & Monteagudo 2014; Pascual Huerta 2014). Conversely, the MP joint is only subjected to a very low DF moment during the propulsive phase, with a DF motion of approximately 30°, counteracted by the plantar muscles and the passive structures of the joint. It is also noticeable that the DF of the ankle and MT joints during gait are about 4° and 8°, respectively, which means that most of the DF motion of the foot corresponds in fact to the MT joint and not to the ankle joint.

The similarity between subjects with respect to the descriptive parameters allowed three different gait patterns to be identified in the subjects participating in the experiment. Most of the differences between the three patterns correspond to the frontal and transverse planes, which agree with the observations of previous work focused on the ankle joint (Simonsen & Alkjær 2012). The main difference observed in the sagittal plane corresponds to a wider range of motion of the ankle joint during the midstance phase for pattern 2. In the frontal plane, the main differences are found in the MP joint, with a higher range of motion for pattern 3, and a smaller EV peak moment for pattern 2 and also in the ankle joint, with a smaller IN peak angle for pattern 3. Finally, in the transverse plane, a higher range of motion occurs in the MT and MP joints for pattern 2,

with a significantly higher peak AB moment at the ankle joint, and to a lesser extent at the MT joint.

Therefore, subjects from pattern 2 use a wider DF/PF range of motion in the ankle, which becomes a higher AB moment at the end of the midstance phase. This could be clinically relevant, as these subjects might be exposed to a higher risk of developing ankle disorders. This fact could explain why some subjects develop joint degeneration with ageing and others do not. Further investigation is required through follow-up studies to check for a relationship between gait pattern 2 and the development of ankle disorders. The outcome of gait re-education of subjects from pattern 2 should be investigated in such cases.

Results from this study suggest that the dynamics of a patient after an intervention or treatment should be compared with the dynamics of healthy subjects belonging to the same gait pattern, as there is no unique normal gait pattern. Pattern classification has been shown to be possible by looking at just 5 parameters, 4 of them related to the transverse plane, and using Equations (1) and (2).

The present study nevertheless has some limitations. The joint moments calculated do not take into account the contact frictional forces, as a pressure platform was used for the kinetic analysis; however, a comparison of joint moments at the ankle from previous works (Hunt et al. 2001) calculated without neglecting the frictional forces suggests that the magnitude of these forces do not significantly affect the joint moment values. Furthermore, results are limited to describing the behaviour of healthy adult male subjects with normal FPI, and cannot be generalised to elderly, paediatric, female or symptomatic populations. Furthermore, the foot joint dynamics described in this paper are constrained to walking; other activities (running, jumping, etc.) might present different patterns that should be investigated. Finally, the description presented

is constrained by the model considered, allowing direct comparison only with data obtained from the use of an analogous model and reference posture.

The results from this study may serve as a basis for future studies to investigate the changes in the dynamics of the foot joints arising from various situations, such as different FPI. The small SD achieved through the control of the subjects' characteristics will be helpful to distinguish smaller differences with respect to the group of target subjects to be investigated.

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Appendix A. Foot dynamics description

A careful interpretation of the dynamics of the foot joints considered is described afterwards in each plane of motion.

DF/PF dynamics. The contact phase (CP) corresponds to ankle PF, allowing the sole of the foot to land on the floor, subjected to a very low moment (most of the body weight is still supported by the antagonist foot). The MP joint at the initial contact shows some DF that decreases as the sole of the foot lands (free motion, no external moment applied to the joint), while the MT joint flexion angle remains approximately constant, subjected to an increasing but very low moment. Subsequently, once the sole of the foot has landed on the floor, both the ankle and MT joints dorsiflex, subjected to an increasing DF moment (the body weight is increasingly supported by this foot), and the MP joint flexion angle remains quite constant while it is subjected to an increasing (although small) DF moment. This period corresponds to the midstance phase (MSP). Finally, in the propulsion phase (PP), both flexion angle and moment at both the ankle and MT joints decrease, and the MP joint dorsiflexes while it is subjected to an increasing moment till the onset of the swing phase, when the moment decreases, returning to zero.

IN/EV dynamics. The CP starts with the ankle in an IN angle that decreases as the sole of the foot lands on the floor, subjected to an increasing EV moment (because of the lateral location of the CoP), till a slightly everted posture is achieved. The behaviour of the MT joint during this phase is similar, although within a smaller angle range because of its lower mobility. The MP joint also shows some IN at the initial contact, which

turns into a final everted angle as the sole of the foot lands (free motion). Subsequently, during the MSP both the ankle and the MT joints slightly invert, especially in the last period, when the EV moments decrease after having achieved their maximal value at half the MSP (location of the CoP becomes centred); and the MP remains approximately constant after an initial small inversion, although it is subjected to an increasing EV moment. Finally, in the PP, both the ankle and the MT joints keep inverting as the joint moments become inverted until the onset of the swing phase, when the moments decrease until they disappear; and the MP joint slightly everts subjected to an increasing EV moment until the onset of the swing phase, when the moment decreases, returning to zero.

AB/AD dynamics. The CP starts with the ankle and MT joints in a slightly adducted angle that increase shortly and finally decrease as the sole of the foot lands on the floor till achieving a neutral AB/AD posture, both joints being subjected to an approximately null AB/AD moment. Conversely, the MP joint shows some AB at the initial contact, which disappears as the sole of the foot lands (free motion). Subsequently, during the MSP the ankle and MP joints slightly adduct, subjected to a very low AB moment, while the MT joint remains approximately constant under a very low AD moment. Finally, in the PP the ankle and the MT joints adduct until the onset of the swing phase, when the ankle abducts and the MT joint angle remains constant, coinciding approximately with a peak AD moment; conversely, the MP joint clearly abducts, subjected to a very low AB moment with a peak at the onset of the swing phase.

Appendix B. Description of Gait patterns

Plots of the mean DF/PF, AB/AD, and IN/EV joint angles and moments across subjects of each gait pattern identified, as a function of time, are shown for each foot joint in the

following Figures B1 to B6.

--- Insert Figures B1 to B6 here ---

The differences in the dynamics of each foot joint among patterns are described below.

Pattern differences at the ankle joint. Curves of angles and moments in the DF/PF plane present a similar profile for all patterns, but with higher DF and PF peaks in pattern 2, i.e. a wider range of angles during the MSP. In the IN/EV plane, pattern 2 shows a later time of the peak EV angle and a higher peak EV moment because of a more lateral location of the CoP, and pattern 3 has a smaller IN angle peak in the PP. Regarding the AB/AD plane, the curve profile of the joint angles differ slightly among patterns, with the AB peak being higher for pattern 3, and being located in the last part of the MSP in pattern 2, in contrast to patterns 1 and 3. This more abducted posture of the ankle in the last part of the MSP generates a higher AB moment in pattern 2.

Pattern differences at the MT joint. Curve profiles in the DF/PF plane are analogous, with a smaller angle at the final contact in pattern 1, and a slightly higher peak moment. Some differences among patterns can be identified in the IN/EV plane: smaller EV angles are observed in pattern 1; a higher peak EV angle, a higher angle at the initial contact (so that no IN angle increase is observed in the CP) and a smaller peak IN moment can be seen in pattern 2; and a smaller peak IN angle in the PP and slightly smaller peak EV moment in pattern 3. Finally, the curve profiles of pattern 2 in the AB/AD plane show higher initial and final contact angles, and a peak AB moment because of the more abducted posture of the ankle in the last part of the MSP of subjects in pattern 2.

Pattern differences at the MP joint. In the DF/PF plane, curve profiles are quite similar, with a smaller initial contact angle in pattern 3 and a smaller peak DF moment in

pattern 2. Several differences can be observed in the IN/EV plane: no peak EV angle is observed at the end of the CP in pattern 2 while it shows the highest eversion angles in the PP with a smaller peak EV moment, and smaller initial IN contact angle; and pattern 3 shows the highest peak EV angle at the end of the CP. As regards the AB/AD plane, pattern 2 shows higher initial and final AB contact angles, providing a higher motion range, and pattern 1 is subjected to the smallest peak AB moment.

Disclosure statement

This article has no relevant Conflict of Interests.