Bending and Torsional Moments - A new measuring system for gait analysis

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Abstract

The Laboratory of Biomechanics of the University of Applied Sciences Münster developed a new measuring system to analyze bending and torsional moments of the foot in shoes. The betois (bending torsion insole system) system allows mobile measurements of multidimensional loads on the foot during movements. A special developed software (MERECS Engineering GmbH, Steinfurt, Germany) realizes the data acquisition, automatically heel strike detection and analysis. The accuracy of the heel strike detection could be confirmed with a synchronously executed insole pressure measurement. To get information about characteristic bending and torsional moments on the foot in shoe during walking norm data from 53 healthy subjects were recorded in a zero-drop shoe. The characteristic bending curves of measuring points proximal to metatarsophalangeal joints one (MTP I) and five (MTP V) and distal to processus calcaneus (heel) demonstrate that alternating moments occur on foot during gait cycles.

Furthermore, betois data recorded while walking and jogging on a treadmill were compared to analyze different effects on bending and torsional moments during both conditions. Maximum dorsal extension moments do not show significant differences between walking and jogging. However, maximum plantar flexion moment during walking is significantly ($p<0.001$) smaller than the maximum plantar flexion during jogging. As a result the alternating bending load also shows significant ($p<0.001$) differences between walking and jogging movements.

1 Introduction

Several measuring systems are used for gait analysis, e. g. plantar pressure insole systems, force plates, and video cameras. Load analysis of the foot in shoe are only performed with single pressure sensors or pressure insole systems. Both obtain only one-dimensional load acting perpendicular to the sensors' surfaces and perpendicular to the bottom of the foot, respectively. Complex kinematic marker systems are used to achieve a more detailed insight in multi-dimensional movements. However, none of the mentioned devices enable bending and torsional loads acting on the foot in shoes. Because these kinds of loads are of great interest for several orthopedic diseases, e.g. diabetic mellitus, hallux valgus or foot fractures [1], the Laboratory of Biomechanics at the University of Applied Sciences in Münster (Germany) developed a new measuring device for gait analysis. The betois (bending torsion insole system) system obtains bending and torsional moments acting at the foot in shoes during movements. Five measuring locations on a flexible layer (0.4 mm; 18Cr9Ni; Record Metall Folien GmbH, Mühlheim a.M., Germany) enable the measurement of multi-dimensional deformations of the insole system and the corresponding moments. To see how bending and torsional loads at the heel and on different measuring points at the forefoot look like we analyzed 53 healthy subjects and collected norm data. Furthermore the different influences of walking and jogging on bending and torsional loads were analyzed.

2 Methods

2.1 The bending-torsion-insole-system

The betois system consists of three units. The insoles, a couple of analogue/digital converter with Bluetooth interfaces and a software for data acquisition and analysis. The insoles consist of a flexible stainless steel layer which is shaped in a way that realizes a cantilever on medial and lateral forefoot. Thereby the cross-talk between single measuring locations can be prevented. Strain gauges where applied and interconnected on both, bottom and upper side of the layer to measure bending as well as torsional deformations and to differentiate between these kinds and disturbances such as tension and compression loads. Sensors are placed proximal to metatarsophalangeal joints one (MTP I) and five (MTP V), proximal to distal interphalangeal joints one (DIP I) and five (DIP V), and distal to processus calcaneus (heel) (see ***Figure 1***).

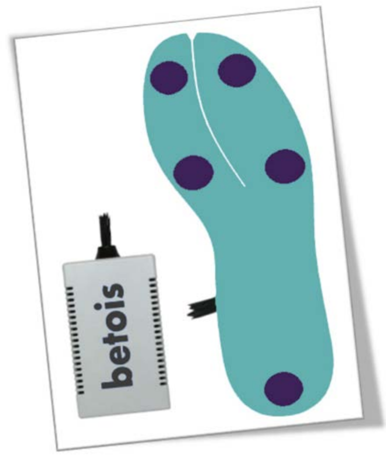

Figure 1 betois (bending torsion insole system) system with five measuring points and A/D- converter.

Measuring locations were calibrated individually for bending and torsion with weights ranging from 5 g to 1000 g. Measuring locations were fixed separately, unilateral and horizontal. To realize loading conditions comparable to conditions during walking the MTPs and DIPs were fixed proximal to measuring location and the heel measuring location at the distal end. The load was introduced on reversed side.

Data acquisition and wireless data transmission to a computer are ensured by four-channel analogue-to-digital converter with Bluetooth interfaces (16 bit, 125 Hz, ME-Meßsysteme GmbH, Henningsdorf, Germany).

Data acquisition and analysis are processed by special developed software (MERECS Engineering GmbH, Steinfurt, Germany). Strain gauges signals are converted into bending and torsional moments based on calibration data provided in the software. Function control of measuring points can be performed in a live view and data recording can be started out of it.
Recorded strides were automatically detected. Therefore the measuring signal is filtered with a low pass filter (Butterworth, 20 Hz, 2. order) to eliminate signal noise. The derivation of the filtered signal is calculated. Time of local maxima gradients of the measured signal are calculated at the derivation curve. Every stride can be classified by one or two positive maxima. Only positive maxima were regarded and out of them those which are higher than 50 % of the average of all local maxima found in the signal. If two maxima occur within a time of 0.46 seconds only the first one is considered. For each of the remaining maxima the minimum in the original curve within the previous 0.18 seconds is determined. The point in time for each calculated minimum corresponds to the point in time of the initial heel strike. If necessary, the automatically calculated heel strike can be adjusted manually. After detection of heel strikes the measured strides were normalized to 100 % gait cycle (101 data points) and averaged. Standard deviation is also calculated and presented together with the mean curve in a graph. Only strides consisting of a predefined duration (0.45 seconds and 1.2 seconds) are considered for average calculation.
The accuracy of the algorithm for automatically stride detection was validated with synchronously executed pressure insole measurement (300 Hz, medilogic®, T&T medilogic Medizintechnik GmbH, Schönefeld, Germany). Therefore, the pressure insole was worn on top of the betois system in a neutral shoe (Samba, Adidas AG, Herzogenaurach, Germany). Both measuring systems were connected to a 5 V synchronization channel. 30 gait cycles were recorded during walking on a treadmill (OrthoCalis, Sprintex, Kleines Wiesental, Germany). Pressure data were analyzed with Noraxon Software (U.S.A. Inc, Arizona, USA) and strides detected for every rise (and fall) of total pressure above (beneath) 1 N/cm². Deviations between the pressure data and the automatically stride detection of the betois software were within one sample of A/D conversion.

2.2 Characteristic bending and torsional curves

To get norm data for bending and torsional moments at the foot in shoes fifty three healthy subjects (33 m, 20 f) between 20 and 59 years (38 ± 11 years) were analyzed (subjects gave informed consent). People with malposition of the feet, lower limb disorders or functional restrictions of the lower limb were excluded. All subjects walked at self-selected speed in a flexible zero-drop shoe (Hattory LC, Saucony/Stride Rite Europe BV) on a treadmill and betois data were recorded. Data of 30 gait cycles were collected, normalized to 100 % of gait cycle (101 data points) and averaged. Data were recorded with GSV-Multi_v1_27 Software (ME measuring systems GmbH) and analyzed using *Matlab* 7.11.0 (R2010b). ***Figure 2*** (in results) shows characteristic courses of bending and torsional moments during whole gait cycle.

2.3 Differences between walking and jogging

To investigate differences on bending and torsional moments between walking and jogging fourteen healthy subjects (12 m, 2 f) with a middle age of 29 ± 8 years, a body mass index of 23.9 ± 3.1 kg /m² and shoe size US 10 were analyzed at MTP I and MTP V (people gave informed consent). People with malposition of the feet and systemic disorders associated with functional restrictions were excluded. Subjects wore a neutral shoe (Samba, Adidas AG) performing walking and jogging on a treadmill. Data of 30 gait cycles were collected (GSVmulti, ME-Messsysteme), normalized (Noraxon, U.S.A. Inc.) to 100 % of gait cycle and averaged. Local maxima of bending and torsional moments as well as range and alternating loads were calculated and analyzed by student t-test. ***Figure 3*** (in results) show the differences between walking and jogging for bending moments on MTP I.

3 Results

3.1 Characteristic bending and torsional curves

Figure 2 shows the bending and torsional moments for three different measuring points in the forefoot and at the heel. For bending positive values indicate a dorsal extension moment and negative data a plantar flexion moment. ***Figure 2 a)*** shows the bending moments (Nmm) at MTP I. The bending moment at the MTP I in zero-drop shoes during walking starts with a slight plantar flexion from initial contact until the mid-stance phase. At 38 % of gait cycle the plantar flexion moment changes into a continuously increasing dorsal extension moment with its local maximum at 63 % of gait cycle. Afterwards the dorsal extension moment decreases continuously until zero (70 %). There is no bending load at MTP I until the end of terminal swing phase. Bending moments at MTP V show similar characteristic with less dorsal extension. ***Figure 2 b)*** shows the bending moments at D I over 100 % of gait cycle. In the first 10 % of gait cycle no bending moment can be observed. After that it rises continuously until a local maximum at nearly 60 % of gait cycle. Between ca. 60 % and 75 % the bending moment at D I decreases until zero till the end of the stride. No plantar flexion moment can be observed at D I. Bending moments on D V show similar characteristic with less dorsal extension and a small plantar flexion instead of no bending moment in the first 10 % of gait cycle. ***Figure 2 c)*** shows the bending moment at the heel. The bending moment starts to rise with the beginning of a step (initial heel contact) and reaches its maximum dorsal extension after 15 % of gait cycle. Afterwards it decreases until zero at 60 % of gait cycle and turns into a plantar flexion. There is just a small plantar flexion for about 10 % of gait cycle before moments at the heel comes to zero until the end of swing phase. ***Figure 2 d)*** shows the torsional moments during walking at the heel. Torsional moments are smaller than bending moments. Positive values are equivalent to an eversion and negative values are equivalent to an inversion of the foot. With the beginning of a step the torsional moment corresponds to an inversion with a local maximum at 8 % of gait cycle and changes in an eversion at 13 % of gait cycle and reaches its maximum after 19 % of gait cycle. From 30 % to 70 % there is an inversion again. For the rest of the gait cycle no torsional moments are observed.

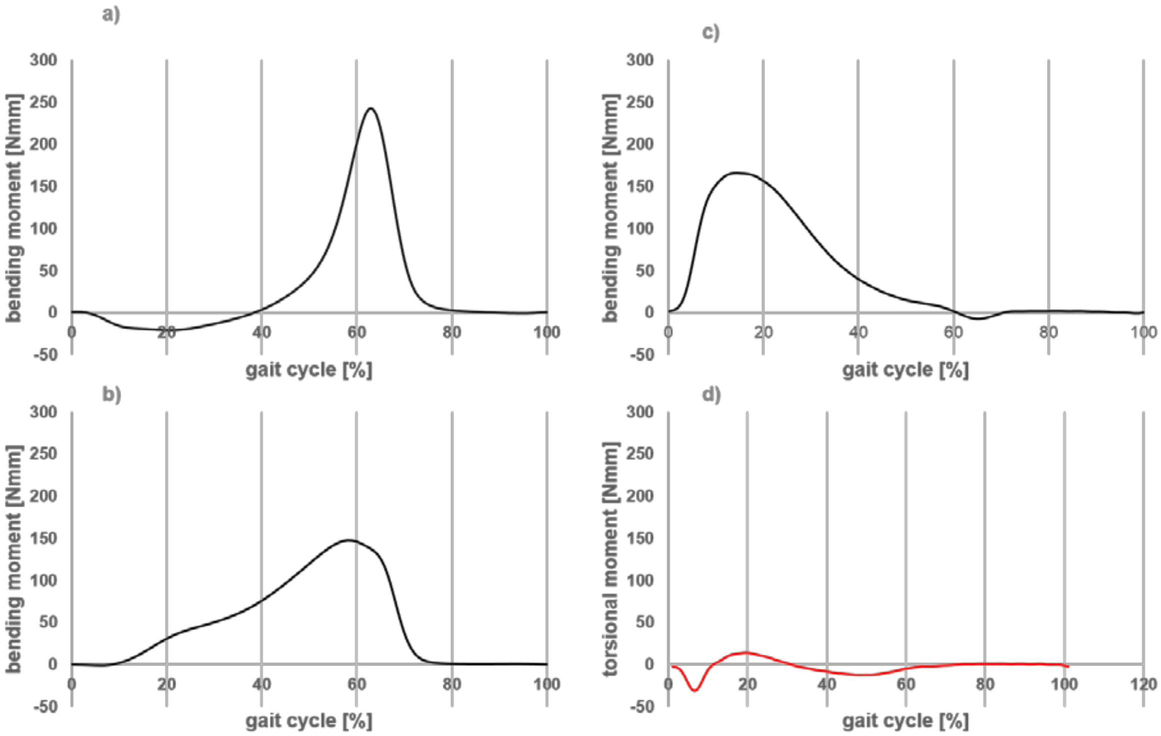

Figure 2 Characteristic loading curves of a) bending moment at MTP I, b) bending moment at DI, c) bending moment at heel and d) torsional moment at heel. Positive bending moments indicate dorsal extension and negative plantar flexion. Positive torsional moments indicate an eversion and negative an inversion.

Bending moments at MTP I and heel and torsional moments at heel show alternating loads. Alternating moments can be described by ***Formula 1***. An alternating bending moment of 0 % means only plantar flexion or only dorsal extension. An alternating bending moment of 100 % means maximum plantar flexion as high as maximum dorsal extension. Alternating bending moments between 0 % and 100 % mean that plantar flexion and dorsal extension both occur but varies in strength.

Formula 1 Calculation of alternating moments.

$$AM_{b/t} = 200 * min\ \left(\frac{|M_{\min}|}{|M_{min}| + |M_{max}|}; \frac{|M_{max}|}{|M_{min}|+|M_{max}|}\right)$$

AM	alternating moment
b/t	bending / torsional
min	minimum
M_{min}	minimum of bending/ torsional moment
M_{max}	maximum of bending / torsional moment

3.2 Differences between walking and jogging

In contrast to the recording of the characteristic loading curves walking and jogging were analyzed using a neutral shoe (Samba, Adidas). ***Figure 3*** shows the results of this comparison. ***Figure 3 a)*** shows the maximum dorsal extension (positive values) and maximum plantar flexion (negative values) averaged over all subjects for both conditions. Maximum dorsal extension moments do not show a significant difference between walking and jogging on a treadmill (walking: 179 Nmm; jogging: 177 Nmm). However, maximum plantar flexion moment for walking is significant (p<0.001) smaller (-79 Nmm) than the maximum plantar flexion during jogging (-117 Nmm). Based on this significant difference, the alternating bending load (see ***Figure 3 b)***) also shows significant (p<0.001) differences between walking and jogging movements. The alternating bending load during jogging is 23 % higher than during walking.

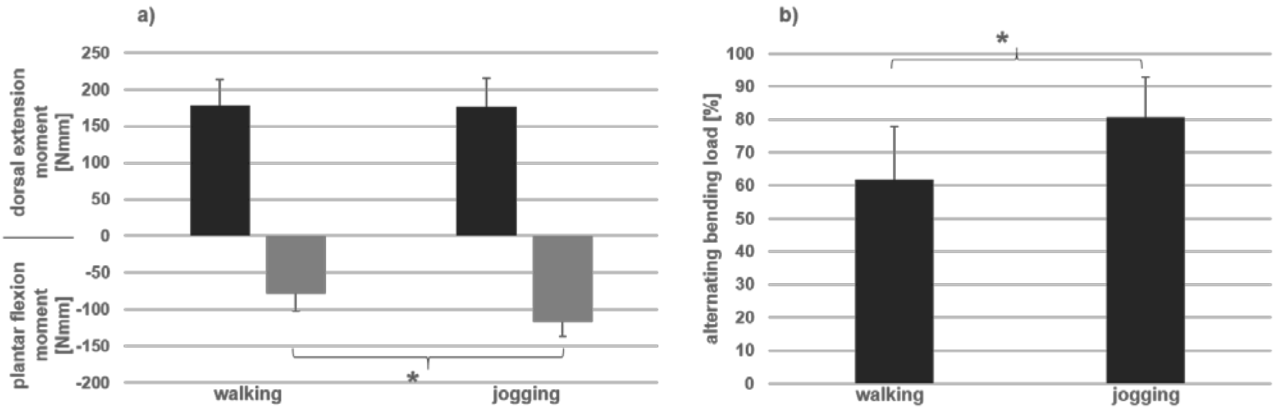

Figure 3 Differences between walking and jogging at MTPI. a) Maximum of plantar flexion and dorsal extension; b) alternation bending loads. (* p<0.001)

4 Discussion and Conclusion

The betois system contains with a software that does not acquire data only but also automatically detects heel strikes. The comparison to manual heel strike detection based on a threshold value analysis of total plantar pressure confirmed the automatic algorithm of the betois software. There is no need to adjust the calculated heel strikes manually for walking movements. Recording bending and torsional moments of 53 healthy subjects provide first norm data for five measuring points. During walking bending moments at MTP I and V occur first in form of plantar flexion and after first third of gait cycle as dorsal extension moments. So alternating stress acting on the forefoot can be observed. Based on known definitions for different phases of gait cycle [2] bending moments at heel show dorsal extension over whole duration of stance phase and a small plantar flexion in first 10 % of swing phase. So alternating stress acting on the heel can be detected, too. We also observe alternating torsional moments on the heel. It is known that alternating loads can influence orthopedic diseases. The betois system can be used to monitor alternating loads on the foot in different shoes and with different orthopedic devices. The torsional moment starts with the beginning of the gait cycle with an inversion and changes after 10% of gait cycle into an eversion for about 20 % bevor it changes back into an inversion until the end of stance phase and turn zero during swing phase. This progress also confirms alternating torsional loads on the foot. Further investigations have to show if this parameter is suitable to assess gait instability.

The comparison of bending and torsional moments for walking and jogging shows significant differences for plantar flexion moment on MTP I but not for dorsal extension. The plantar flexion increases by nearly 50 %. This and the resulting difference in alternating bending loads involve an increase in stress on the forefoot during jogging.

Plantar flexion occurs during walking from beginning of stance phase and reaches into terminal stance phase with a maximum in the middle stance phase. The rising plantar flexion could represent a higher stabilizing function of the forefoot while having ground contact. One focus for running shoe design is on the forefoot stability in stance phase [3], so forefoot stability is an important element of gait analysis during jogging.

For the first time the betois system allows the mobile and valid measurement of multi-dimensional loads in shoes during movement. It provides an addition to already established measuring systems for gait analysis and extends possibilities of investigations of foot and shoe interactions. Therefore the bending torsion insole system enables the proof of effectiveness of orthopedic devices like rocker soles and off-loading shoes or e.g. running shoes.

References

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