Comparison of inverse dynamics calculated by two- and three-dimensional models during walking

Tine Alkjaer a,*, Erik B. Simonsen a, Poul Dyhre-Poulsen b

a Department of Medical Anatomy, Section C, The Panum Institute, University of Copenhagen, Blegdamsvej 3, 2200 Copenhagen, Denmark
b Department of Medical Physiology, The Panum Institute, University of Copenhagen, Copenhagen, Denmark

Accepted 01 November 2000

Abstract

The purpose of the study was to compare joint moments calculated by a two- (2D) and a three-dimensional (3D) inverse dynamics model to examine how the different approaches influenced the joint moment profiles. Fifteen healthy male subjects participated in the study. A five-camera video system recorded the subjects as they walked across two force plates. The subjects were invited to approach a walking speed of 4.5 km/h. The ankle, knee and hip joint moments in the sagittal plane were calculated by 2D and 3D inverse dynamics analysis and compared. Despite the uniform walking speed (4.53 km/h) and similar footwear, relatively large inter-individual variations were found in the joint moment patterns during the stance phase. The differences between individuals were present in both the 2D and 3D analysis. For the entire sample of subjects the overall time course pattern of the ankle, knee and hip joint moments was almost identical in 2D and 3D. However, statistically significant differences were observed in the magnitude of the moments, which could be explained by differences in the joint centre location and joint axes used in the two approaches. In conclusion, there were differences between the magnitude of the joint moments calculated by 2D and 3D inverse dynamics but the inter-individual variation was not affected by the different models. The simpler 2D model seems therefore appropriate for human gait analysis. However, comparisons of gait data from different studies are problematic if the calculations are based on different approaches. A future perspective for solving this problem could be to introduce a standard proposal for human gait analysis. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Human locomotion; Biomechanics; Two- and three-dimensional analysis; Walking; Inverse dynamics

1. Introduction

Human walking has been analysed by the inverse dynamics approach based on externally measured kinematics of the body segments in combination with measurements of the ground reaction forces acting on the segments. Most often, sagittal joint moments are estimated by using two-dimensional (2D) inverse dynamics analysis [1]. This is a simple procedure, which requires only one camera to record the movement, and only a few markers placed on anatomical landmarks to define the 2D positions of the joint centres [2].

Recently, several three-dimensional (3D) inverse dynamics analyses of human gait have been presented [3–8]. 3D gait analysis is more complicated. To identify the body segments in space, at least three markers must be attached to each segment and each marker has to be recorded from at least two different camera angles in order to reconstruct the 3D position. The 3D positions of the joint centres then have to be estimated and body segment reference systems must be constructed in order to identify the orientation of the segments in the global reference system. Furthermore, it is possible to construct anatomically based joint axes to which the joint moments can be referred. The argument for referring the joint moments to anatomical joint axes is that the subjects may walk with their segments rotated internally or externally in relation to the plane of progression [9]. In such cases the sagittal plane of the segments does not coincide with the sagittal plane of the global reference system.
Few studies have discussed the differences between 2D and 3D joint moments [5,8,10]. Eng and Winter (1995) [5] concluded that 3D sagittal joint moments were similar to those from previously reported 2D studies. However, the study did not compare the 2D and 3D joint moments directly and therefore explains little about the specific differences between the two approaches.

Remarkable inter-individual differences in the joint moment patterns have been reported in the literature [11–14]. However, the majority of the studies used 2D inverse dynamics models, and it is therefore possible that the variations could be explained by limitations of the 2D approach. Information about how the different models affect the shape and magnitude of the joint moments is relevant for the investigator when deciding whether a 2D or 3D approach should be considered for gait analysis.

Accordingly, the purpose of the present study was to compare sagittal joint moments calculated using 2D and 3D inverse dynamics approaches, respectively, in order to answer the following questions: (a) Are the joint moment profiles from the 2D analysis similar to those from the 3D analysis?; (b) How do the different joint axes affect the joint moments?; (c) Is the 2D approach appropriate for studies of human walking?

To ensure the reliability of the comparison between the 2D and 3D joint moments, the kinematic, the kinetic and the anthropometric data used in the models were obtained from the same experiments.

2. Methods

Fifteen healthy male subjects gave their informed consent to participate in the experiments, which were approved by the local ethics committee. The mean age was 30 (21–42) years, the body mass 83.7 (65–89) kg and the body height 1.81 (1.74–1.89) m. All subjects were healthy and without any history of lower extremity pathology.

The subjects were asked to walk across two force platforms (AMTI, OR6-5-1) at a speed of 4.5 km/h. The speed was controlled by photocells, which made it possible to teach the subject to walk at approximately 4.5 km/h.

The subjects were dressed in a tight black suit and 15 small spherical reflecting markers (12 mm diameter) were placed according to the marker set-up described by Vaughan et al. [9]: On the head of the fifth metatarsal, the heel, the lateral malleolus, the tibial tubercle, the lateral femoral epicondyle, the greater trochanter, the anterior superior iliac spine and on the sacrum. All subjects wore lightweight flexible shoes with a thin and flat sole.

Five video cameras (Panasonic WV-GL350) operating at 50 frames per second were used to record the movements. The cameras were gen-locked to avoid phase shift during exposure. Synchronisation between the video signals and the force plate signals was obtained electronically using a custom-built device. The device put a visual marker on one video field from all cameras and at the same time triggered the analogue to digital converter that sampled the force plate signals at 1000 Hz. The subjects initiated the data sampling and the synchronisation when they passed the first photocell.

The video sequences were digitised and stored on a PC. 3D co-ordinates were reconstructed by direct linear transformation using the Arial Performance Analysis System (APAS).

Prior to the calculations, the position data were digitally low-pass filtered by a fourth order Butterworth filter with a cut-off frequency of 6 Hz, and the 1000 Hz force plate signals were resampled at 50 sps.

A 2D and 3D biomechanical model were used to calculate flexor and extensor net joint moments about the ankle, knee and hip joint. The 2D inverse dynamics model was based on the free-body segment method [2]. 2D joint moments were computed in MATLAB in which the code presented by Van den Bogert and de Koning [15] was modified. The markers placed on the anatomical landmarks on the lateral malleolus, the lateral femoral epicondyle and the greater trochanter defined the ankle, knee and hip joints about which the 2D joint moments were calculated.

3D inverse dynamics were also computed in MATLAB with a program implementing the formulas presented by Vaughan et al. [9]. In the 3D model, the joint centres were estimated on the basis of reference data based on X-ray measurements from one subject combined with anthropometric measurements from each of the subjects. The positions of the joint centres were then predicted relative to a reference system with origins at the reflecting markers on the ankle, knee and sacrum, respectively [9]. A unit vector segment reference frame was calculated for the foot, the shank and the thigh. First, the resultant 3D joint moments were calculated in the segment-based reference frames of each segment, meaning that the sagittal ankle, knee and hip joint moments were expressed about the mediolateral axes of the foot, the shank and the thigh. In the following these moments will be referred to as ‘3D-global’ because the unit vectors of each segment were expressed in terms of the global reference frame. The 3D-global joint moments were then expressed in an anatomically based reference system [16]. The anatomical axes for the flexor and extensor moments of the ankle, knee and hip joint were the mediolateral axes of the segment reference frames of the shank, the thigh and the pelvis, respectively. The moments about the
anatomical axes will just be referred to as ‘3D’ joint moments.

The anthropometric data from Chandler et al. [17] and anthropometric measurements from each subject were used to calculate segment masses, moments of inertia and centres of mass in both the 2D and the 3D model.

The differences between the joint centres and the joint axes used in the 2D and the 3D model should result in differences in the joint moments. To test how the differences in joint centre locations affected the 2D and the 3D joint moments the $x, y$ co-ordinates of the predicted joint centres from the 3D model were used in the 2D model instead of the marker positions after which the 2D joint moments were re-calculated.

Six gait cycles were normalised and averaged for each subject. Normalisation was performed in MATLAB by interpolating data points to form 500 samples for each gait cycle. Only the stance phase was analysed. The joint moments were normalised to body mass:100 (Nm/kg:100). Ensemble averages were then calculated for the entire group using the individual subject means ($n = 15$ subjects).

Coefficients of variation (CV) were calculated as the mean standard deviation over the entire ensemble average and expressed as a percentage of the range of the mean data values [18]. CV were used to determine intra- and inter-individual variations.

The Wilcoxon Signed Ranks Test [19] for paired samples was used to test statistical differences between 2D and 3D net joint moments. The parameters used for the statistical analysis were means of peak joint moments about the ankle, knee and hip joint from six gait cycles from each person. The level of significance was set to 5%.

3. Results

3.1. Intra- and inter-individual variations

The average walking speed for the whole group was $4.53 \pm 0.06$ km/h. For each of the subjects, the walking speed across the six analysed gait cycles varied 1.3%.

The intra-individual variation was largest in the knee joint moment (CV = 8.2% (2D) and 8.5% (3D)) compared to the ankle joint moment (CV = 4.0% (2D) and 4.6% (3D)) and the hip joint moment (CV = 6.4% (2D) and 5.4% (3D)). The SD of the joint moments was similar in both 2D and 3D. The small differences in the CV between 2D and 3D were therefore due to differences in range.

The inter-individual variations were also largest in the knee joint moment (CV = 23% (2D) and 21% (3D)) compared to the ankle (CV = 9% (2D and 3D)) and the hip joint moment (CV = 13% (2D) and 11% (3D)).

3.2. Comparisons of 2D and 3D joint moments

The general shapes of the 2D and 3D joint moment patterns about the ankle, knee and the hip were very similar (Fig. 1), but the statistical analysis of differences in the joint moments between the 2D and 3D model showed significant differences with respect to the magnitude of the moments (Fig. 2). A dorsi flexor moment was seen in the 3D analysis whereas the 2D calculation showed almost complete plantar flexor dominance about the ankle joint. The peak dorsi flexor moment was significantly smaller in 2D than in 3D (2 $\pm$ 1.5 vs.

![Fig. 1. Joint moments (Nm/kg:100) about ankle, knee and hip joint. Zero on the x-axis indicates heel strike and 100 indicates toe off. Positive values indicate ankle dorsi flexor, knee extensor and hip flexor joint moments. The curves represent 2D (solid lines), 3D (open circles), 3D-global (squares) and re-calculated 2D (crosses) joint moments.](image)

Fig. 2. Peak values of 2D and 3D joint moments (Nm/kg·100). Black bars represent 2D and white bars represent 3D joint moments. Values are means ± 5D (n = 15). Positive values indicate ankle dorsi flexor, knee extensor and hip flexor moments. The ankle and the hip peak joint moments were measured in the first and the second half of the stance phase. The two peak knee extensor moments were measured in the first and the second half of the stance phase and the peak knee flexor moments were measured in the middle of the stance phase. Asterisks indicate a significant difference between 2D and 3D peak joint moments (P < 0.05).

7 ± 6 Nm/kg·100, P = 0.00278). The peak plantar flexor moment was significantly larger in 2D than in 3D (−183 ± 17 vs. −155 ± 16 Nm/kg·100, P = 0.0009) (Fig. 2).

There was no significant difference between the 2D and the 3D peak knee extensor moment in the first half of the stance phase (45 ± 25 vs. 50 ± 23 Nm/kg·100). The knee joint flexor moment in the middle of the stance phase was larger in 2D (−34 ± 20 Nm/kg·100) than in 3D (−18 ± 20 Nm/kg·100) (P = 0.00115). The peak knee extensor moment in the second half of the stance phase was significantly smaller in 2D than in 3D (25 ± 8 vs. 44 ± 14 Nm/kg·100, P = 0.0009).

For the hip joint moment, the flexor moment in the second half of the stance phase was larger in 3D (104 ± 23 Nm/kg·100) than in 2D (65 ± 18 Nm/kg·100) (P = 0.0009), while no difference was found between the 2D and 3D hip extensor moments (Fig. 2).

3.3. Effects of joint centres and joint axes

When the marker positions, which defined the foot, the shank and the thigh in the 2D model, were replaced by the 2D positions of the estimated joint centres used in the 3D model, the differences between the re-calculated 2D moments and the 3D moments about the ankle and the hip joints disappeared (Fig. 1). The re-calculated 2D knee joint moment was similar to the 3D knee joint moment in the first half of the stance phase, but there was still a difference in the peak knee flexor and peak knee extensor moment in the second half of the stance phase (Fig. 1). These differences disappeared when the re-calculated 2D knee joint moment was compared to the 3D-global knee joint moment (Fig. 1). In contrast, there were no differences between the 3D-global hip and ankle joint moments and the 3D ankle and hip joint moments expressed about the anatomical axes (Fig. 1).

4. Discussion

The purpose of this study was to compare joint moments during walking calculated by a 2D and a 3D inverse dynamics method. The 2D and 3D calculations were based on kinematic and kinetic data from the same experiments to ensure that the comparison was reliable. The results showed that the general shapes of the 2D and 3D joint moments were very similar. The intra-individual variations of the joint moments were smaller than the variation between individuals in both 2D and 3D. The knee joint moment showed the largest variation both intra- and inter-individually. Some subjects walked with extensor dominance about the knee joint throughout the entire stance phase, while other subjects walked with almost complete knee flexor dominance. Remarkable individual variations in the joint moment patterns have been reported in previous studies, especially large variations in the knee joint moment [11–14].

The comparison of the 2D and the 3D peak joint moments showed significant differences in magnitude. However, the joint moments differed systematically in magnitude and therefore the inter-individual variations in the 2D and 3D joint moments were identical. A number of factors, e.g. walking speed and footwear, influence the joint moment pattern [20,21]. In the present study the subjects walked at the same speed and wore the same type of footwear; the variations could therefore not be due to differences in these factors. As suggested by Pedotti 1977, the inter-individual variations in the joint moment patterns could possibly be due to different motor control strategies of the walking pattern [12]. It is still unclear how the control mechanisms involved in human walking are working [22] and
further investigations in this field will be helpful in the explanation and interpretation of the variations in the walking patterns.

The different joint centres and joint axes to which the moments were referred could explain the differences between the 2D and the 3D joint moments. A re-calculation of the 2D joint moments using the estimated position of the joint centres from the 3D model instead of the position of the skin markers, removed the differences between the 2D and 3D ankle and hip joint moments. The 3D ankle joint moment was smaller than the 2D ankle joint moment because the estimated position of the ankle joint centre in the 3D model was on average 2.0 cm anterior to the marker placed on the lateral malleolus which resulted in a smaller 3D ankle joint moment. The larger 3D hip flexor moment could also be explained by the different locations of the hip joint centre in the two models. On average, the estimated position of the 3D hip joint centre was 1.5 cm anterior and 2.7 cm proximal to the greater trochanter. Hence, the 3D hip joint centre resulted in a larger hip flexor moment compared to the 2D hip flexor moment. Other 3D gait studies have also reported larger hip flexor moments compared to those reported in 2D studies [5,8,10].

The differences between the 2D and the 3D knee joint moment could only partly be explained by differences in joint centre locations in the two models. When comparing the re-calculated 2D knee joint moment with the 3D-global knee joint moment the differences disappeared. In contrast, the use of anatomical axes did not affect the 3D joint moments about the ankle and hip. The relative rotation of the segments was therefore small during the stance phase.

The following conclusions can be made on the basis of the results of this study: Despite significant differences between peak values of the 2D and 3D joint moments, the overall time course patterns of the moments were identical. The different joint centres and axes used in the 2D and the 3D joint moment calculations affected the magnitude of the moments but not the inter-individual variation of the joint moment profiles. The use of anatomical joint axes in the 3D model affected the knee joint moment but not the ankle and hip joint moments. The simpler 2D approach seems therefore appropriate for gait analysis. However, it should be emphasised that the peak values of the joint moments are dependent on the chosen calculation model, which makes it difficult to compare joint moments calculated by different approaches.

The existing normative data on human walking are not conclusive. One way of increasing the knowledge of human walking would be to introduce a standard proposal for human gait analysis, which would make it possible to compare gait data from different studies.

References