Manuscript Details

Manuscript number	GAIPOS_2018_1070_R1
Title	Leaving hip rotation out of a conventional 3D gait model improves discrimination of pathological gait in cerebral palsy: a novel neural network analysis
Article type	Full Length Article

Abstract

Background: Complex clinical gait analysis results can be expressed as single number gait deviations by applying multivariate processing methods. The original Movement Deviation Profile (MDP) quantifies the deviation of abnormal gait using the most trusted nine dynamic joint angles of lower limbs. Research question: Which subset of joint angles maximises the ability of the MDP to separate abnormal gait from normality? What is the effect of using the best subset in a large group of patients, and in individuals? Methods: A self-organising neural network was trained using normal gait data from 166 controls, and then the MDP of 1923 patients with cerebral palsy (3846 legs) was calculated. The same procedure was repeated with 511 combinations of the nine joint angles. The standardised distances of abnormal gait from normality were then calculated as log-transformed Z-scores to select the best combination. A mixed design ANOVA was used to assess how removing the least discriminating angle improved the separation of patients from controls. The effect of using the optimal subset of angles was also quantified for each individual leg by comparing the change in MDP to the independent FAQ levels of patients. Results: Removal of hip rotation significantly ($p<0.0005$) increased the separation of the patient group from normality (ΔZ-score 0.24) and also at FAQ levels 7-10 (ΔZ-score 0.38, 0.27, 0.22, 0.14). The MDP of individual patients changed in a wider range of -4.65 to 1.12 Z-scores and their change matched their independent FAQ scores, with less functional patients moving further from, and more functional patients moving closer to normality. Significance: In existing gait databases we recommend excluding hip rotation from data used to calculate the MDP. Alternatively, the calculation of hip rotation can be improved by post-hoc correction, but the ultimate solution is to use more accurate and reliable models of hip rotation.

Keywords	gait, movement deviation profile; sensitivity analysis; neural network; hip rotation
Taxonomy	Biomechanics of Gait, Cerebral Palsy

Corresponding Author	Gabor Barton
Corresponding Author's Institution	Liverpool John Moores University
Order of Authors	Gabor Barton, Malcolm Hawken, Mark Scott, Michael Schwartz

Suggested reviewers	Jim Richards, Wolfgang Schollhorn

Submission Files Included in this PDF

File Name [File Type]

1 Cover letter v2.docx [Cover Letter]

Response to reviewer comments.docx [Response to Reviewers]

2 Highlights.docx [Highlights]

3 Title page with author details v2.docx [Title Page (with Author Details)]

4 Manuscript v2.docx [Manuscript File]

5 Figures.docx [Figure]

6 Conflict of interest.docx [Conflict of Interest]

Date: 07/02/2019

For the attention of Dr Tishya Wren, Associate Editor of Gait and Posture

Dear Tishya,

Please find attached our responses to the reviewer comments related to our manuscript now entitled "**Leaving hip rotation out of a conventional 3D gait model improves discrimination of pathological gait in cerebral palsy: a novel neural network analysis"**. We thank the reviewers for their insight, they have certainly helped to improve clarity of the paper.

All authors were fully involved in the study and preparation of the manuscript and the material within has not been and will not be submitted for publication elsewhere.

Yours sincerely,

Gabor

Prof. Gabor Barton MD PhD
Professor of Clinical Biomechanics
Research Institute for Sport and Exercise Sciences
Liverpool John Moores University
Tom Reilly Building, Byrom Street, Liverpool, L3 3AF, UK
tel: +44 (0)151 9046263 email: G.J.Barton@ljmu.ac.uk
Personal profile | Biomechanics group

__**Comments from the editors and reviewers, followed by responses by the authors (indented):**__

-Editor

-Reviewer 1

This appears to be a sound article (if slightly depressing) concluding measurements of hip rotation are so variable that the MDP performs more intuitively if you leave this variable out.

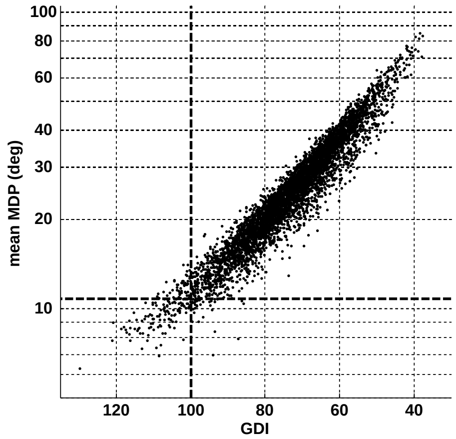
> Thanks for the comment.

A feel this could have been conveyed by a shorter technical note but using a full article does allow some more data to be presented which might be useful.

> We agree, the complexity of the analysis warranted a full paper.

I'm a little puzzled, given the authors, that the same analysis wasn't also conducted using GDI. Assuming the analysis was automated and assuming a similar result it would have been an almost trivial exercise to report this finding. In the absence of this analysis I think it would be useful to include some discussion as to whether this finding is likely to be specific to this one index or more generalisable.

> Two sentences were added to the text at the end of Discussion (and two entries to the References): "Given the high correlation (r^2=0.927) [3] between the MDP_{mean} and the Gait Deviation Index (GDI) [11] and the high correlation (r=0.995) between the GDI and the Gait Profile Score (GPS) [12], it is likely that leaving out hip rotation would also improve the sensitivity of the GDI and GPS. However, the tendency of the MDP_{mean} to provide a more normal score to some patients than the GDI with an unusual distribution, further detailed investigations are warranted to evaluate how variable selection affects the performance of the GDI and GPS."
>
> For the benefit of the reviewer, below is the scatter plot of MDP_{mean} against the GDI from [3], showing the unusual distribution.



An interesting follow on would be to look at whether the findings of any intervention studies might be more conclusive if hip rotational less indices were used as the primary outcome measure, but I agree that this is beyond the scope of this study (maybe this issue could also be flagged in the discussion).

> While this is definitely what we expect to see, it would be a speculative statement and we agree that it is beyond the scope of this paper.

-Reviewer 2

The title needs to include “cerebral palsy” as this may not be universal for different conditions

> Thanks, the title has been modified to “Leaving hip rotation out of a conventional 3D gait model improves discrimination of pathological gait in cerebral palsy: a novel neural network analysis”

Abstract

I would like to see some clinical reasoning behind leaving out hip rotation improves the ability to discriminate between groupings.

“In existing gait databases we recommend excluding hip rotation from data used to calculate the MDP.”

> We believe the results of the analysis show clearly that hip rotation can be regarded as a hindrance that blurs the set of gait results and reduces the ability of the gait index to separate patients from controls, and so the only solution to improve the usefulness of the gait index is to omit the offending variable (unless better quality data are available derived from a refined 3D model). Clearly, hip rotation is part of the clinical interpretation of gait results which assesses all joint angles, and so any information contained in the hip rotation angle contributes to the clinical decision-making process. Gait analysts are trained not to place too much emphasis on the hip rotation angle due to its documented shortcomings.

Again needs to specify CP

> The methods of the Abstract specify that all patients had cerebral palsy and together with the modified title it is now clear that the study is solely about CP.

Main text

Throughout needs to make clear that this is only for CP data at key points within the paper which I leave to the authors discretion

> Cerebral palsy (or CP) is mentioned in the new title, Abstract, Methods, Discussion (twice) and the Conclusions. We believe that the study’s focus on cerebral palsy is clear with the new title and without any further mention of the condition.

Discussion

Again I would like to see some clinical reasoning behind leaving out hip rotation improves the ability to discriminate between groupings. Was this due to errors in measurement or such variability so that the measure reduced sensitivity?

> We have discussed why hip rotation, often contaminated by inaccurate thigh wand alignment, is a weak contributor to the gait index in the Discussion: “The low reliability and high error of hip rotation angle [6], possibly due to its dependence on correct thigh wand alignment may explain why leaving this variable out significantly improves the separation of patients from controls.”. Further details are found in the cited reference.

Would other marker models have the same issues? You seem to touch on this but this could be more explicit. Could hip rotation be in fact a very useful measure which is clinically important between the different patient categories?

> We suggested using a more refined marker model in the Discussion (“… a 3D gait model using a functional joint centre of the hip and functional axis of the knee [8] results in a better

fit of the model to the patient's anatomy thereby improving the accuracy of measured hip rotation.") and Conclusions ("The ultimate solution will be the wider use of more accurate methods to reconstruct hip joint rotation during gait."). The readers can follow up the reference [8] which provides further details. This reference was chosen specifically because their method has been implemented in major gait analysis software packages since its publication.

We do not question the importance of hip rotation, indeed we suggested how its measurement should be improved so that it can be included in gait indices. When the measured hip rotation angles cannot be improved retrospectively then removing them from the dataset is the only solution.

HIGHLIGHTS

- The Movement Deviation Profile calculates the deviation of gait from normality
- Excluding hip rotation from the 9 trusted angles improves separation from normality
- The effect is small but significant in 3846 legs of children with cerebral palsy
- The effect on individual legs of patients can be much larger
- We recommend omitting hip rotation from the calculation of gait summary measures

Leaving hip rotation out of a conventional 3D gait model improves discrimination of pathological gait in cerebral palsy: a novel neural network analysis

Barton GJ[1*], Hawken MB[1], Scott MA[1], Schwartz MH[2]

1 Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, United Kingdom, L3 3AF
2 Department of Orthopaedic Surgery, University of Minnesota, Minneapolis, USA
3 Gillette Children's Specialty Healthcare, St. Paul, USA
* Corresponding author, email g.j.barton@ljmu.ac.uk

INTRODUCTION

The results of an instrumented gait analysis typically include multiple time series of joint kinematics and kinetics. Angles, moments and powers of the pelvis, hips, knees and ankles are calculated from three-dimensional motion capture data combined with ground reaction forces. All curves from the left and right legs are plotted against their normalised gait cycle over reference curves taken from a normal gait database to facilitate comparisons. Gait analysts are trained to build an internal representation of the patient's abnormal gait using the complex results, which then leads to hypothesising biomechanical cause-and-effect relationships among the inter-linked body segments as they move during walking.

Clinicians, whose focus extends beyond the biomechanics of gait, are often overwhelmed by the complexity, and inevitably technical terminology, of gait reports. They often voice their requirement for simplified representations of gait results, but clearly the expectation is to remove the complexity while also retaining the rich information content of the data. Successful attempts have been made to address this seemingly impossible challenge by developing simplified summaries of gait results, often in the form of a single number or gait index, which represents the patient's deviation from normality [1,2].

The use of gait indices has been increasing as part of a clinical gait analysis, informed by a steady increase of publications on this topic. Using the search term "gait index" OR "gait indices" produces the first PubMed hit in 1996 and 334 hits in 2018. One of the methods related to gait indices, among those published more recently, described the Movement Deviation Profile (MDP) [3], which is the deviation of a patient's movement from normality, calculated using a self-organising artificial neural network. Gait indices, including the MDP, have addressed a genuine need, but several fundamental questions related to their use remain to be answered. By default, the MDP uses those nine dynamic joint angles that are trusted most by gait analysts, but the relative contributions of the individual variables to maximising effectiveness is not known. Another important point is that the evaluation of gait indices has focused on large groups of patients, even though the clinical use of such indices lies in the monitoring of gait deviation in individual patients.

The primary aim of this study was to identify the optimal subset of variables used to calculate the MDP. This aim is achieved by systematically eliminating gait variables and examining the effect on the separation between pathological gait and normality. A secondary aim was to highlight the effects of using the optimised subset of variables on the MDP of individual patients in addition to the effect on groups of patients.

PATIENTS/MATERIALS and METHODS

Pelvic and hip angles in all three planes, knee flexion/extension, ankle plantar/dorsiflexion, and foot progression angles were used, generated using either the Vicon Clinical Manager or Vicon Plug-in-gait model from 1923 patients with cerebral palsy (CP) with Functional Assessment Questionnaire (FAQ) scores between 10 and 6 [4], and 166 typically developing controls. Approval was obtained from the local ethics committee and written consent was obtained from all participants prior to testing.

The neural network was first trained with control data, and then produced the mean deviation from normality (MDP_{mean}) over the gait cycle for both legs of each patient (3846 legs). Variables were then eliminated systematically, covering all 511 combinations of the nine variables (1 combination of 9 variables, 9 combinations of 8 variables, 36 combinations of 7 variables, 84 combinations of 6 variables, 126 combinations of 5 variables, 126 combinations of 4 variables, 84 combinations of 3 variables, 36 combinations of 2 variables and 9 combinations of 1 variable). For each of the 511 combinations the average of the log-transformed 3846 MDP_{mean} values was mean-corrected and normalised to the SD of log-transformed MDP_{mean} values of controls providing a standardised measure of distance (Z-scores) between the patients and controls.

The data were then examined to determine the optimal combination of variables which gives the highest separation of patients from controls. To test how the separation improved in patients with a range of movement problems, the gait deviation of patients grouped by their FAQ scores (10-6) using the optimal subset of eight variables (8V) was compared to the deviation using all 9 variables (9V). A 2 × 5 ([8V, 9V] × [FAQ10, FAQ9, FAQ8, FAQ7, FAQ6]) mixed design ANOVA was performed on the MDP_{mean} values calculated from the more affected leg and the less affected leg of each patient [5]. Data from the more affected and less affected leg has to be analysed separately because the biomechanical coupling means that the gait curves are not independent. Post hoc testing of the significant interaction consisted of simple main effect analysis, where the alpha level corrections for multiple comparisons were carried out in accordance with the recommendations of Maxwell and Delaney [5]. Two separate one-way between-subject ANOVAs were used to compare the FAQ levels for 8V and 9V, for which the alpha levels were corrected to 0.025 (0.05/2). To determine where the specific differences were between the FAQ levels, corrected independent t-tests (0.05/10 = 0.005) were performed to compare 8V to 9V at each separate FAQ level.

In addition to the effect of using the optimal variables in groups of patients, the effect on each 3846 legs of the 1923 patients was also analysed. Specifically, the change in each leg's MDP_{mean} towards or away from normality was examined. To test if the optimal set of variables resulted in a change of patients' calculated deviation from normality that matches their independently measured functional capacity, the FAQ score distribution was compared between those who moved towards and away from normality.

RESULTS

Overall, reducing the number of variables from nine to 1 reduced the mean deviation of the group of patients from normality (Figure 1). As indicated by a moving-average with a window size of 50 (bold solid line), the Z-scores reduce slowly and gradually until only 3 variables are left (the mean Z-score with 9 to 4 variables was 3.34, 3.31, 3.23, 3.12, 2.99 and 2.84 respectively). After that the deviation dropped rapidly with combinations of 3, 2 and 1 variables (means of 2.62, 2.27 and 2.05). The reduction is not continuous though; there are sharp changes with up to about 1 Z-score between combinations of variables.

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

When examining the effect of eliminating one and two variables, the highest separation (i.e. highest Z-score) of the patient group from normality was not when using all nine variables (diamond in Figure 2). Elimination of the hip rotation angle (cross and circles in Figure 2) increased the separation of patients from controls most, and elimination of the foot progression angle reduced the separation most (triangles in Figure 2) when eliminated on their own or paired with other variables. When both hip rotation and foot progression angle were excluded (square in Figure 2), the opposite effects on separation from normality neutralised each other and so this combination was not analysed further. When hip rotation was excluded from the seven or eight variables used, the Z-scores were all higher (mean±SD = 3.48±0.08) than the Z-score with all nine variables (3.34, diamond in Figure 2). The highest Z-score (3.58) out of all 511 combinations was found when hip rotation was eliminated, and this improved the separation of the patient group from normality by a Z-score of 0.24.

----------- Figure 2 here

Splitting the patients in five categories (FAQ 10-6) with progressively reducing function, showed a monotonically increasing separation from normality when using all nine variables to calculate the MDP_{mean} Z-scores (grey curves in Figure 3), similarly to the original MDP study [1]. When using the most important eight variables, the separation from normality increased in each FAQ category (black curves in Figure 3). Additionally, the increase in separation was progressively greater in the lower FAQ categories (by 0.14, 0.22, 0.27, 0.38 and 0.44 ΔZ-scores in FAQ 10-6 respectively when considering the 1923 more affected legs (Figure 3a). A similar pattern of results was found when considering the less affected 1923 legs (0.21, 0.26, 0.27, 0.35 and 0.38 ΔZ-scores in FAQ 10-6 respectively), although the separation from normality was naturally less.

When considering the more affected legs, there were significant main effects for the number of variables used (8V vs. 9V, $F_{1,\ 1918} = 154.81$, $P < 0.0005$), FAQ level ($F_{4,\ 1918} = 84.22$, $P < 0.0005$) and a significant interaction ($F_{4,\ 1918} = 7.78$, $P < 0.0005$). Both of the corrected one-way between-subjects ANOVAs showed significant differences. When comparing between the five FAQ levels for 8V, there were significant increases between each more affected leg MDP_{mean} value as FAQ severity increased. One exception to this was between levels FAQ7 and FAQ6. This pattern of differences was the same for 9V values. At each level of FAQ the more affected leg MDP_{mean} values 8V were significantly higher than 9V.

Similar statistical results were found when evaluating the less affected legs. There were significant main effects for the number of variables used (8V vs. 9V, $F_{1,\ 1918} = 192.16$, $P < 0.0005$), FAQ level ($F_{4,\ 1918} = 86.21$, $P < 0.0005$) and a significant interaction ($F_{4,\ 1918} = 3.14$, $P = 0.014$). Both of the corrected one-way between-subject ANOVAs showed significant differences. When comparing between the five FAQ levels for 8V, there were significant increases between each less affected leg MDP_{mean} value as FAQ severity increased apart from between levels FAQ7 and FAQ6. This pattern of differences was the same for 9V values. At each level of FAQ the less affected leg MDP_{mean} values 8V were significantly higher than 9V.

----------- Figure 3 here

To explore how the calculated gait deviation of each patient is affected by using only the best eight variables, the pairwise differences of log-transformed MDP_{mean} Z-scores were calculated for each patient between using all nine variables and leaving out hip rotation. The main chart in Figure 4 is a stem-and-leaf plot which visualises how much each 3846 leg moved left (towards normality, blue arrows) and right (away from normality, red arrows) as a result of leaving out hip rotation. The size of the arrowheads is proportional to the length of the arrow which indicates where the patient moved from and where they ended up on the transformed MDP scale. For each arrowhead the gait deviation is the sum of its stem and leaf values. For reference, the distribution of the Z-scores with vertical mean and SD lines is plotted in grey using all nine variables and in black using eight variables without hip rotation. The small histogram of Figure 4 shows the distribution of changes in Z-scores due to leaving out hip rotation. A median change of 0.45 was found within the range of -4.65 to 1.12 with 1st and 3rd quartiles of -0.06 and 0.73 respectively.

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

Figure 5 shows that those who ended up with more abnormal MDP_{mean} Z-scores after leaving out hip rotation (red arrows in Figure 4) were indeed in lower FAQ categories (i.e. further away from normality) than those whose Z-scores moved towards normality (blue arrows in Figure 4). This confirms that by leaving out the confounding variable of hip rotation, patients move towards or away from normality according to their independent FAQ score which is a validated measure of their functional abilities i.e. a proxy for “normality”. Note that the blue and red bars in the histogram of Figure 5 were normalised to the number of legs which moved left (1036) and right (2810) on Figure 4, respectively, and then normalised to the number of legs in each FAQ category. The grey bars are the number of legs in each FAQ category and were set to 100% for reference. Such normalisation was necessary for a comparative visualisation of the lower shifted distribution of FAQ categories for patients whose MDP_{mean} Z-scores moved away from normality (in red) and towards normality (in blue) compared to the original FAQ distribution (in grey).

----------- Figure 5 here

DISCUSSION

When examining the overall effect of systematically removing from the default nine variables through all 511 combinations, a small effect was found on the ability of the MDP_{mean} to separate a large group of CP patients from normality. The performance of the MDP degraded markedly though with 3 or fewer variables. Conversely, using more than 9 joint angles with similar information content is unlikely to increase separation considerably. In fact, including further joint angles not much trusted by gait specialists (e.g. knee varus/valgus or shank rotation) would likely introduce more noise than useful information content which is expected to reduce the separation of patients from controls.

The low reliability and high error of hip rotation angle [6], possibly due to its dependence on correct thigh wand alignment may explain why leaving this variable out significantly improves the separation of patients from controls. Leaving foot progression angle out moved the patient group closest to normality suggesting that this variable is an important determinant of gait abnormality.

As an alternative to leaving out hip rotation from the calculation of a gait index like the MDP, the accuracy of hip rotation can be improved. If an analysis of gait results in an existing database using conventional 3D gait models is necessary, then the accuracy of hip rotation can be improved by post-hoc mathematical realignment of the thigh wand marker [7]. When starting a new gait database, a 3D gait model using a functional joint centre of the hip and functional axis of the knee [8] results in a better fit of the model to the patient’s anatomy thereby improving the accuracy of measured hip rotation.

The effect on the MDP_{mean} of leaving out hip rotation angle differed across FAQ scores in that more affected patients (lower FAQ) are better separated from normality than less affected patients (higher FAQ). This suggests that the abnormality of hip rotation cannot be captured well in more affected patients resulting in apparently more normal hip rotation than what would match their FAQ score. Removing this conflicting variable therefore increased their separation from normality, matching their MDP_{mean} better to their FAQ level. It is a documented limitation of the thigh's 3D conventional biomechanical model that only a proportion of the femur's dynamic axial rotation is measured by the rotation of a thigh wand attached to the skin [9,10] due to the considerable shearing movement of soft tissues between the bone and skin. This mechanism may go some way to explain why greater abnormal hip rotation is less detectable than a small abnormality.

The second highest MDP_{mean} Z-score was found when both hip rotation and knee flexion/extension were eliminated. It may be that changes of the knee angle are linked to changes of other angles and so the normality information contained in knee angles is redundant. Knee flexion/extension is a variable trusted by gait analysts when examining gait angles because it is an easy to comprehend, accurate and reliable angle determined by long bones (femur and tibia). This however does not contradict the suggestion derived from the sensitivity analysis, in that the same information content is available in other curves.

When evaluating a large sample of 3846 legs of CP patients as a group, the difference in Z-scores (0.24) is statistically significant but small between the default nine variables and those eight which maximise separation from normality. This difference however is the summed effect of increased and reduced Z-scores of individuals and so the change at the group level is not a complete reflection of individual changes. A complementary measure of the effect of using the optimum set of variables is to examine the effect on the distribution of the MDP_{mean} values of individual patients. The median of the change in MDP_{mean} Z-scores was 0.45 which is considered a large enough difference as it would move a patient into or even beyond a neighbouring FAQ category (e.g. 0.41 difference between the medians of FAQ 8 and 9 when considering the more affected legs). More importantly, the inter-quartile range of 0.79 and the total range of 5.77 of the changes suggest major effects on some individual patients.

Keeping only the eight most important variables resulted in a shift of the MDP_{mean} for some patients away from normality and others towards normality. Their independent measure of normality, their FAQ scores, showed that the direction of their shift matched the respective distribution of their FAQ scores. This confirmed that removing hip rotation resulted in a subset of gait variables which reflect a patient's deviation from normality more faithfully.

Given the high correlation (r^2=0.927) [3] between the MDP_{mean} and the Gait Deviation Index (GDI) [11] and the high correlation (r=0.995) between the GDI and the Gait Profile Score (GPS) [12], it is likely that leaving out hip rotation would also improve the sensitivity of the GDI and GPS. However, the tendency of the MDP_{mean} to provide a more normal score to some patients than the GDI with an unusual distribution, warrants further investigation to evaluate how variable selection affects the performance of the GDI and GPS.

CONCLUSIONS

A novel sensitivity analysis evaluating the separation of a large group of CP patients from normality using the artificial neural network-based Movement Deviation Profile showed that the hip rotation angle provided by the conventional Vicon Clinical Manager or Vicon Plug-in-gait model is the strongest hindrance out of the nine best joint angles. Removing hip rotation resulted in a relatively small but significant increase in the separation of patients' gait from normality and the changes affecting individual patients are considerably larger.

When applying the MDP to existing gait data from databases using conventional gait models, we advise leaving out hip rotation or to improve its accuracy post-hoc. Such improvements are expected to increase the discriminatory power of the MDP and other widely used gait indices. The ultimate solution will be the wider use of more accurate methods to reconstruct hip joint rotation during gait.

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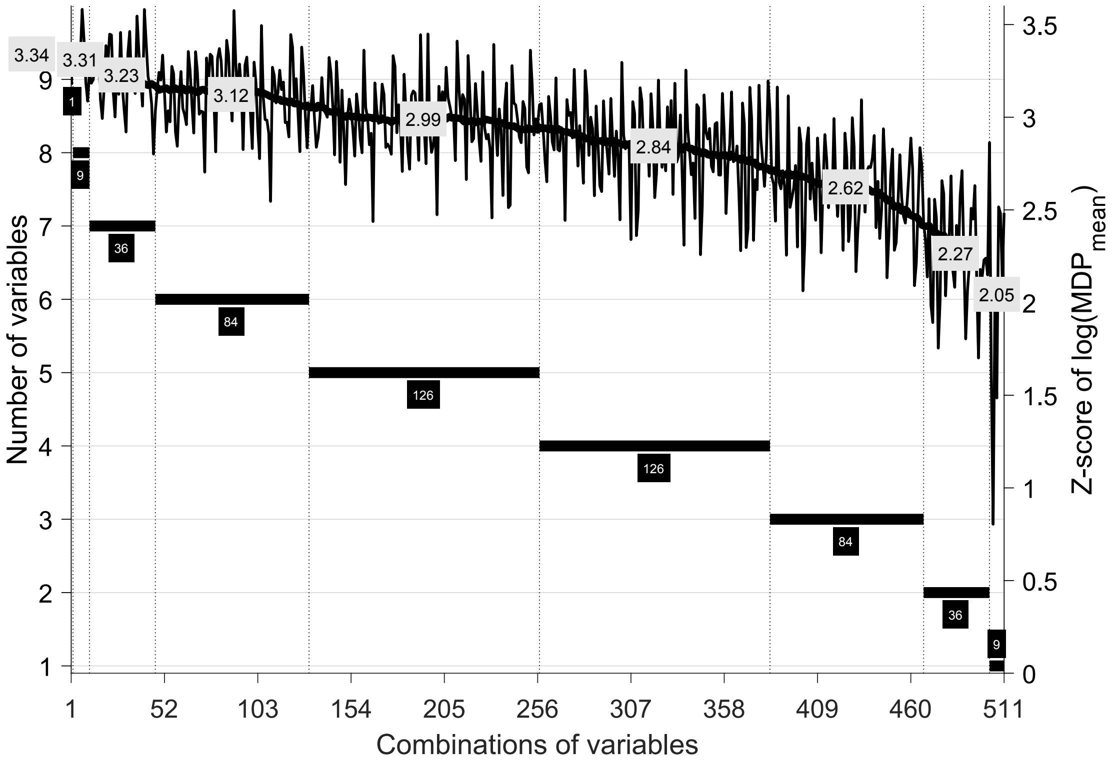
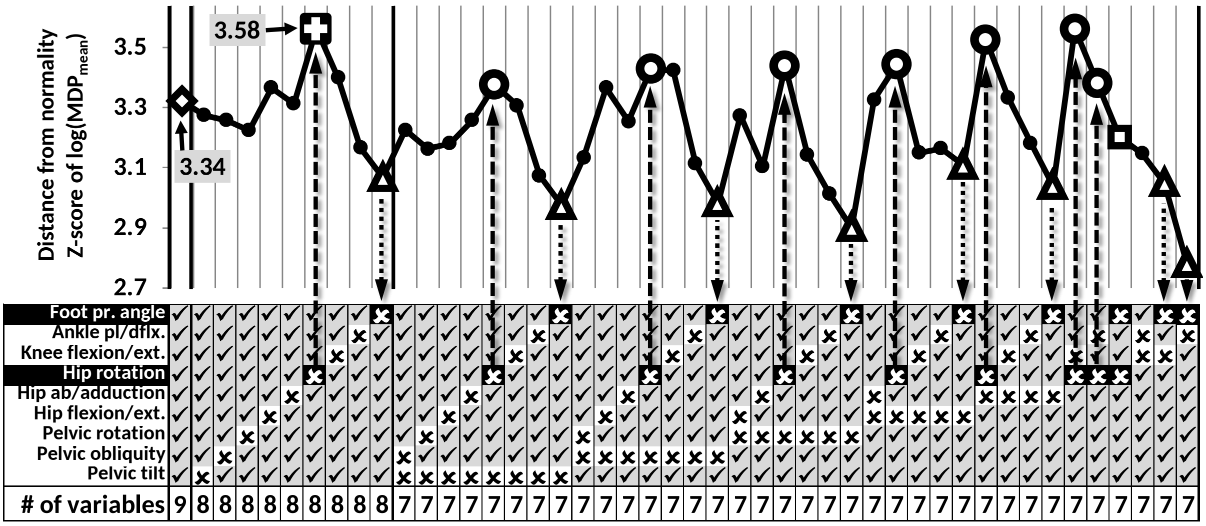
Figure 1



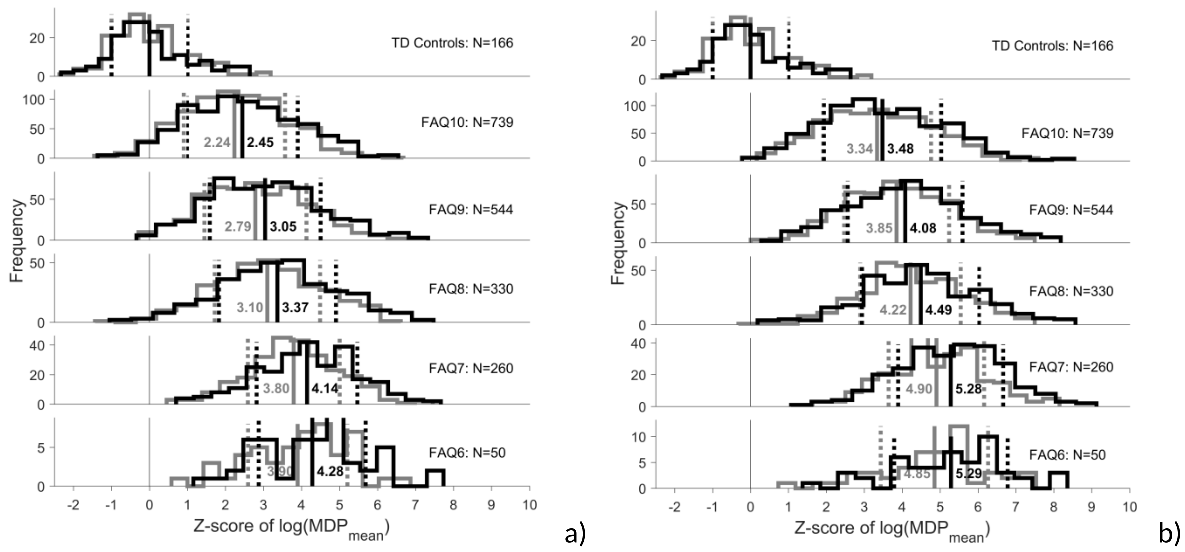
Number of variables
Z-score of log(MDP_{mean})
Combinations of variables
3.34
3.31
3.23
3.12
2.99
2.84
2.62
2.27
2.05
1
9
36
84
126
126
84
36
9
1 52 103 154 205 256 307 358 409 460 511
1 2 3 4 5 6 7 8 9
0 0.5 1 1.5 2 2.5 3 3.5

Figure 2



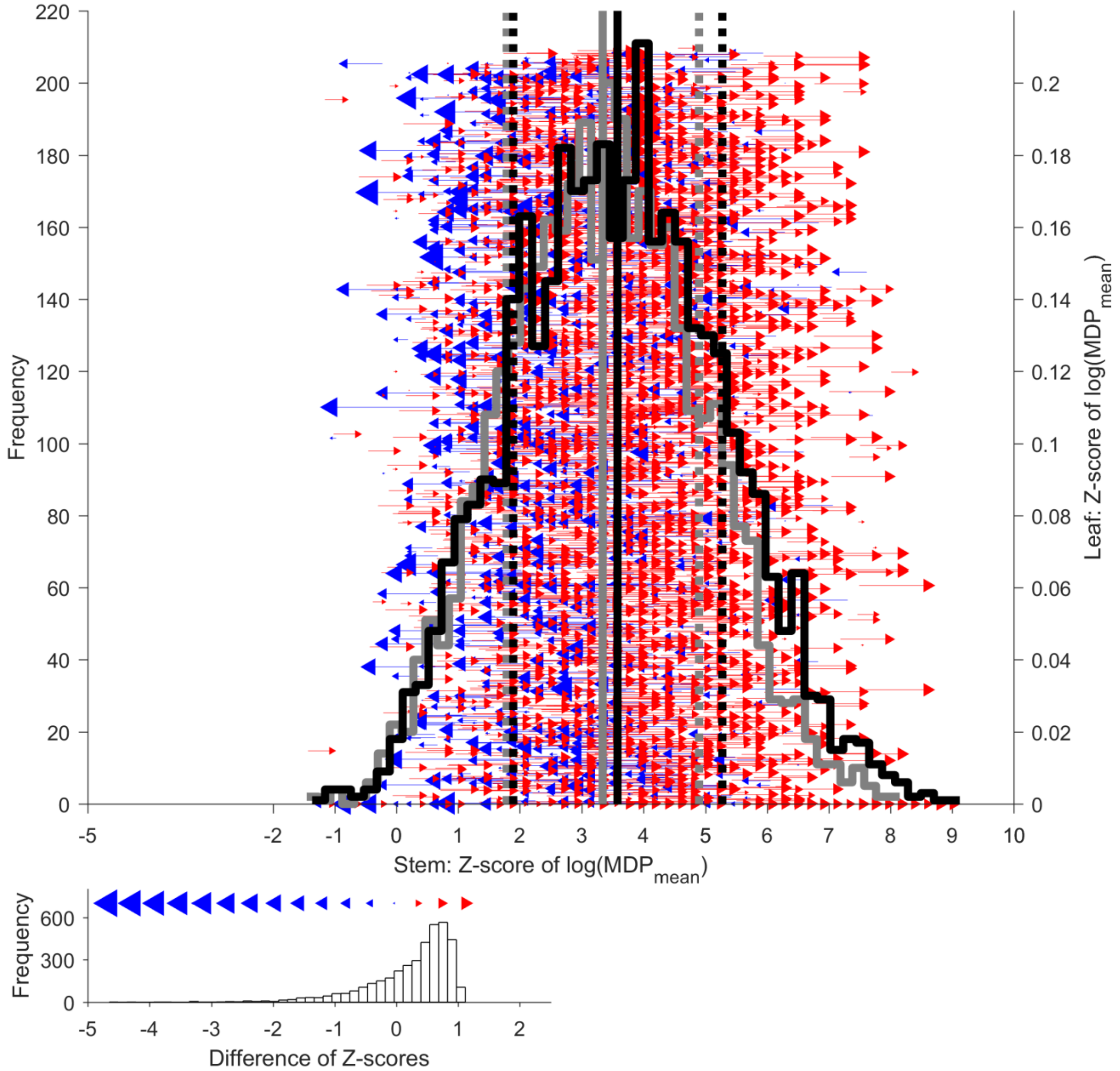
Distance from normality
Z-score of log(MDP$_{mean}$)
3.5
3.3
3.1
2.9
2.7
3.58
3.34
Foot pr. angle
Ankle pl/dflx.
Knee flexion/ext.
Hip rotation
Hip ab/adduction
Hip flexion/ext.
Pelvic rotation
Pelvic obliquity
Pelvic tilt
# of variables
9 8 8 8 8 8 8 8 8 8 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7 7

Figure 3



TD Controls: N=166
FAQ10: N=739
FAQ9: N=544
FAQ8: N=330
FAQ7: N=260
FAQ6: N=50
Frequency
Z-score of log(MDP_mean)
2.24
2.45
2.79
3.05
3.10
3.37
3.80
4.14
4.28
3.34
3.48
3.85
4.08
4.22
4.49
4.90
5.28
4.85
5.29
a)
b)

Figure 4



Frequency
Leaf: Z-score of log(MDP$_{mean}$)
Stem: Z-score of log(MDP$_{mean}$)
220
200
180
160
140
120
100
80
60
40
20
0
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-5
-2
-1
0
1
2
3
4
5
6
7
8
9
10
Frequency
600
300
0
-5
-4
-3
-2
-1
0
1
2
Difference of Z-scores

Figure 5

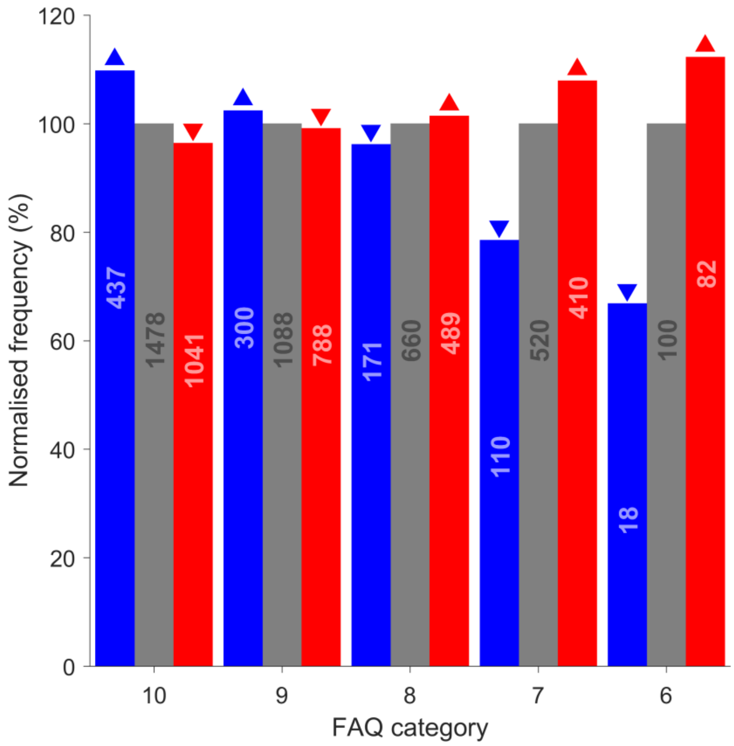

120
100
80
60
40
20
0
Normalised frequency (%)
437
1478
1041
300
1088
788
171
660
489
110
520
410
18
100
82
10
9
8
7
6
FAQ category

Figure captions

Figure 1: The gait deviation of patients (2nd vertical axis) for each combination (horizontal axis) of their nine joint angles (1st vertical axis). The number of combinations with 9 to 1 variables is shown as numbers in black boxes, the mean of Z-scores for 9 to 1 variables is shown as numbers in grey boxes.

Figure 2: Changes of Z-scores when using all nine and combinations of eight and seven variables (✓ and ✖) with the MDP. Highest (○) and lowest (△) separation of patients from controls was found when leaving out hip rotation and foot progression angles respectively (rows with highlighted saltires ✖). When both hip rotation and foot progression angles were eliminated (□), the opposite effects on deviation from normality neutralised each other. Eliminating hip rotation resulted in the highest separation (✚) compared to using all nine variables (◇).

Figure 3: Gait deviations of patients in FAQ 10-6 compared to typically developing controls (TD) considering their a) more affected and b) less affected legs.

Figure 4: Histograms (1st vertical axis) of gait deviations (horizontal axis) with mean (solid lines) and ±SD (dotted lines) using all nine variables in grey, and without hip rotation in black. The stem-and-leaf diagram (horizontal and 2nd vertical axes) visualises how much the gait deviation of each 3846 leg of patients changes after leaving out hip rotation. Each Z-score is the sum of the stem and leaf values. Blue arrows indicate legs which moved closer to normality, red arrows indicate moving away from normality. The length of the arrows and size of the arrowheads are proportional to the change due to leaving out hip rotation. The small histogram shows the distribution of the changes in Z-scores on the same horizontal scale.

Figure 5: After removing hip rotation, those who moved away from normality (in red) show a shift to the right, towards lower FAQ categories with more involvement. Conversely, those who moved closer to normality (in blue) have a distribution shifted towards higher FAQ categories, i.e. closer to functional normality. Red and blue bars were normalised to their respective total numbers and then to the number of legs in each FAQ category, grey bars were normalised to the number of legs in each FAQ category. Absolute number of legs in each FAQ category are shown on the bars.

The authors declare that they have no conflicts of interest.