


## RESEARCH ARTICLE

# Gait function improvements, using Cardiff Classifier, are related to patient-reported function and pain following hip arthroplasty

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**Abstract**

Summarizing results of three-dimensional (3D) gait analysis into a comprehensive measure of overall gait function is valuable to discern to what extent gait function is affected, and later recovered after surgery and rehabilitation. This study aimed to investigate whether preoperative gait function, quantified and summarized using the Cardiff Classifier, can predict improvements in postoperative patient-reported activities of daily living, and overall gait function 1 year after total hip arthroplasty (THA). Secondly, to explore relationships between pre-to-post surgical change in gait function versus changes in patient-reported and performance-based function. Thirty-two patients scheduled for THA and 25 nonpathological individuals were included in this prospective cohort study. Patients were evaluated before THA and 1 year postoperatively using 3D gait analysis, patient-reported outcomes, and performance-based tests. Kinematic and kinetic gait parameters, derived from 3D gait analysis, were quantified using the Cardiff Classifier. Linear regressions investigated the predictive value of preoperative gait function on postoperative outcomes of function, and univariate correlations explored relationships between pre-to-post surgical changes in outcome measures. Preoperative gait function, by means of Cardiff Classifier, explained 35% and 30% of the total variance in change in patient-reported activities of daily living, and in gait function, respectively. Moderate-to-strong correlations were found between change in gait function and change in patient-reported function and pain, while no correlations were found between change in gait function and performance-based function. Clinical significance: Preoperative gait function predicts postsurgical function to a moderate degree, while improvements in gait function after surgery are more closely related to how patients perceive function than their maximal performance of functional tests.

**KEYWORDS**

Activities of Daily Living, Function, Gait, Osteoarthritis, Total Hip Arthroplasty

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## 1 | INTRODUCTION

Osteoarthritis (OA) is one of the leading causes of years lost to disability worldwide, and one of the most common chronic diseases of the musculoskeletal system.<sup>1,2</sup> Beside painful joints and decreased quality of life, patients with hip OA walk more slowly, walk with altered gait pattern characteristics<sup>3,4</sup> that are often reported as limping gait,<sup>5</sup> and have reduced hip muscle strength compared to healthy controls.<sup>6-9</sup> Total hip arthroplasty (THA) is a well-accepted and frequently used surgical intervention for severe hip OA, and is considered one of the most successful orthopedic procedures.<sup>10,11</sup> The literature on THA typically investigates functional capacity using simple performance-based activities such as short and long distance walking, stair negotiation,<sup>12</sup> and/or patient-reported outcome measures.<sup>13</sup> While such measures provide information about function, they fail to provide insight into the objective biomechanics of movement which can be observed by three-dimensional (3D) gait analysis. The extensive datasets generated by instrumented 3D gait analysis are usually reduced into a substantially smaller set of discrete metrics (maximum, range, integral) calculated from selected waveforms. As an example, discrete metrics from 3D gait analysis have demonstrated reduced hip adduction and extension angles in THA patients,<sup>6,14,15</sup> but are these discrete measures of functional importance to the degree where the overall gait function is affected, (i.e., summarized gait pattern and performance), and if so, to what extent? Moreover, such discoveries on discrete metrics may in part be false-positive findings due to multiplicity of potential endless numbers of variables.<sup>16</sup>

The Gait Deviation Index on kinematics and kinetics have been proposed as single scores that summarize overall gait patterns of the patient's kinematics and kinetics, respectively.<sup>17,18</sup> Studies have shown that the Gait Deviation Index is associated with patient reported outcome measures of physical function, pain and quality of life in patients scheduled for THA,<sup>19</sup> and that the preoperative Gait Deviation Index before THA, to some extent, predict the postoperative Gait Deviation Index.<sup>20</sup> However, the responsiveness of the Gait Deviation Index in patients with hip OA has been questioned since no,<sup>21</sup> or only small to moderate improvements in index scores<sup>22</sup> were observed following THA.

The Cardiff Classifier is a novel approach for generating an overall index of gait function, named after the institution where it was developed. Previous applications of the Cardiff Classifier include the differentiation of pathologic gait function seen in individuals with knee OA and healthy controls, and to monitor postoperative recovery following total knee arthroplasty.<sup>23-25</sup> Despite not yet being applied to THA patients, the Cardiff Classifier has potential methodological advantages over the Gait Deviation Index.<sup>26</sup> Opposed to Gait Deviation Index, gait kinematics and kinetics (including ground reaction forces) have typically been included in the single measure of Cardiff Classifier, and all frontal and transverse plane measures at the hip, knee and ankle have been considered. In addition, three of the five most discriminatory biomechanical features found by the Cardiff Classifier in individuals with knee OA are not included in either the

Gait Deviation Index for kinematic or kinetics.<sup>26</sup> Moreover, in total knee arthroplasty patients, the Cardiff Classifier methodology has been found to predict postoperative outcome,<sup>23</sup> and has shown surprisingly strong correlations with patient reported outcome measures.<sup>26</sup> To date, application of the Cardiff Classifier in patients with hip OA, and whether it has any predictive value for post THA outcomes, remains unknown.

Simplifying 3D gait analysis data into a single metric describing the overall gait pattern would be of great value in clinical practice to discern whether the overall gait function is affected and to what extent, and to inform healthcare providers and patients what can be expected in terms of change in gait patterns. Further, knowledge on whether it is patients with the greatest perceived recovery who also have the best biomechanical outcomes, and vice versa, is limited. A comprehensive metric, accounting for interdependencies of biomechanical variables, would facilitate interpretation of results of 3D gait analyses among clinicians, and facilitate monitoring over time and following interventions. Thus, this study aims to (1) quantify and summarize overall gait function using the Cardiff Classifier, (2) evaluate whether this comprehensive gait measure can predict improvements in postoperative patient-reported function and overall gait function 1 year after THA. Secondary, to explore potential relationships between change (pre vs. post THA) in overall gait function by means of Cardiff Classifier versus changes in patient-reported and performance-based function.

## 2 | MATERIALS AND METHODS

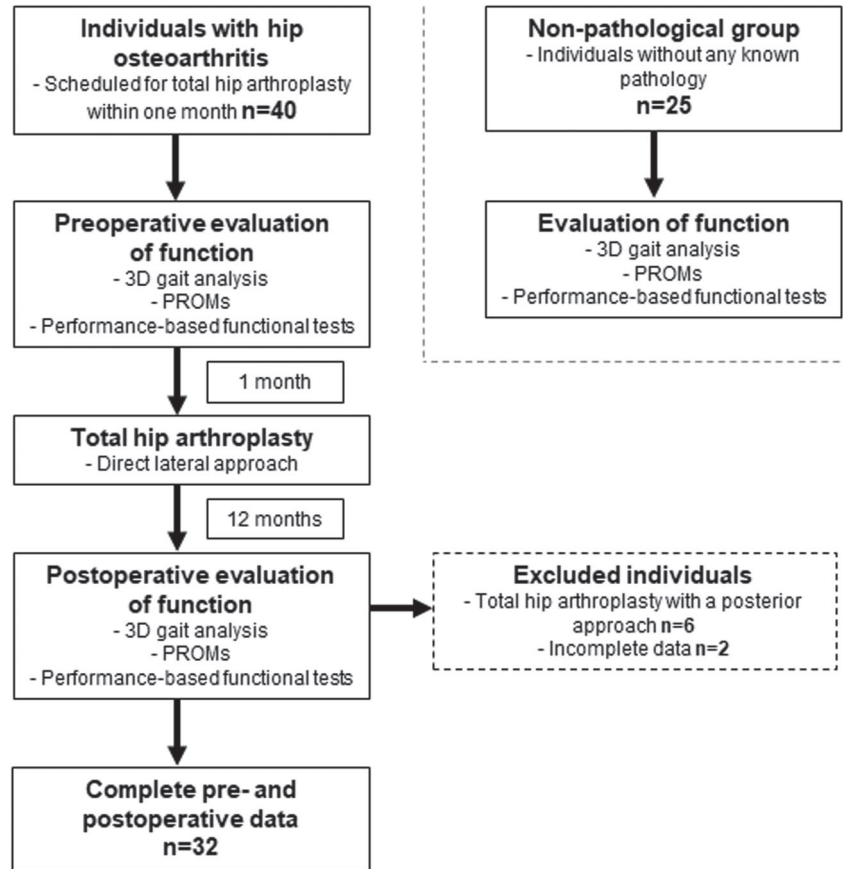
The regional ethical review board in Stockholm, Sweden approved the study (DNR 2010/1014-31/1). All participants provided verbal and written informed consent in accordance with the Declaration of Helsinki.

### 2.1 | Design and reporting

This longitudinal prospective cohort study (level of evidence: II) reports ancillary data on a previously published study on performance-based function, gait and patient-reported function.<sup>27</sup> The study was reported following the "Strengthening the Reporting of Observational Studies in Epidemiology" (STROBE) Statement as a guideline.<sup>28</sup>

### 2.2 | Study participants

Patients with symptomatic hip OA were recruited from two orthopedic departments in Stockholm, Sweden (Ortho Center Löwenströmska Hospital and Karolinska University Hospital) between the years 2011 and 2014 (Figure 1). Inclusion criteria included physician diagnosed primary hip OA; unilateral patient-reported hip symptoms; scheduled for THA within 1 month after baseline evaluation; ability to walk 10 m repeatedly without the use of a walking aid; and ability to

**FIGURE 1** Flowchart of included study participants**TABLE 1** Baseline characteristics of patients with hip osteoarthritis and nonpathological healthy controls included in the study

	Hip osteoarthritis (n = 32)	Nonpathological subjects (n = 25)	Differences between groups p value
Mean age, years (SD)	66.6 (9.2)	65.7 (9.5)	.70
Female, n (%)	23 (72)	16 (64)	.71
Body mass index (kg/m <sup>2</sup> ), mean (SD)	26.7 (3.9)	24.9 (2.9)	<b>.02</b>
Body weight (kg), mean (SD)	76.8 (15.2)	72.8 (12.2)	.29
Height (cm), mean (SD)	16 (9)	171 (8)	.42
Kellgren and Lawrence score (1–4)			
1–2, n (%)	–	NA	
3, n (%)	10 (31)	NA	
4, n (%)	22 (69)	NA	

Note: Bold p value below .05 was considered statistically significant.

understand verbal and written information in Swedish. Exclusion criteria were previous major orthopedic surgery in the lower limbs, severe back pain, rheumatoid arthritis, diabetes mellitus, neurologic disease and/or other conditions affecting walking ability, and a body mass index (BMI) >35. The rationale for excluding participants with a

BMI >35 was to avoid movement artefacts during the gait analyses due to excessive soft tissue. In addition, THA surgery performed with a posterior approach was also an exclusion criterion. Allowing Cardiff Classifier to differentiate pathologic gait function from nonpathologic gait a control group consisting of 25 nonpathological individuals

without any known musculoskeletal disease and/or neurological disorder was included through a convenience sample of acquaintances between the years 2013–2015.<sup>27</sup> The nonpathological group was matched to the hip OA group by gender and age strata across five age groups (Table 1).

### 2.3 | Three-dimensional gait analysis

Two experienced physiotherapists conducted all gait analyses at the Motion Analysis Laboratory at Karolinska University Hospital, Stockholm, Sweden. Study participants were instructed to walk barefoot at self-selected speed along a 10-m long pathway. Kinematic, kinetic, and spatiotemporal parameters were collected using an 8 camera motion system (©Vicon Motion Systems Ltd.) and the Plug-In-Gait full-body model.<sup>29</sup> Good intra-session repeatability has been reported for this model.<sup>30</sup>

### 2.4 | Patient-reported function and pain

All study participants completed the self-administered patient-reported outcome measure Hip Disability and Osteoarthritis Outcome Score (HOOS), a questionnaire divided into five separate subscales; Symptoms, Pain, Function in Activities of Daily Living, Function in Sport, and Recreation, and Hip-related Quality of Life. HOOS is considered reliable for assessing hip-related function and pain, and change over time.<sup>13</sup>

### 2.5 | Performance-based functional tests

Three performance-based functional tests were performed in random order including the Timed Up and Go test,<sup>31</sup> the Five Times Sit to Stand test,<sup>32</sup> and the Single Limb Mini Squat test,<sup>33</sup> all of which have demonstrated good reliability in patients with hip OA.<sup>34,35</sup> Detailed information about test procedures are reported elsewhere.<sup>27</sup> In brief, the Five Times Sit to Stand test was conducted by recording the time required by the participant to stand up from a seated position five times as fast as possible. The Timed Up and Go test was conducted by recording the time it takes the participant to rise from a chair, walk 3 m at a self-selected speed, turn 180°, and return to a seated position. The Single Limb Mini Squat test was performed by recording maximal number of single-leg mini squats in 30 s. Fingertip support for balance was provided by a frame placed in front of the participant.

### 2.6 | Surgical technique and postoperative regimes

Patients with hip OA received a THA with a direct lateral approach as described by Hardinge.<sup>36</sup> The surgeries were performed by five senior orthopedic surgeons from two different hospitals. Patients had no postoperative movement restrictions, allowing full weight-bearing

together with use of an appropriate walking aid, and standard postoperative rehabilitation lasted for a median duration of 2 months after surgery, all according to standard practice at each hospital.

## 2.7 | Cardiff Classifier

Classification of gait patterns using Cardiff Classifier was carried out according to multiple steps (Appendix 1).

### 2.7.1 | Principal component analysis

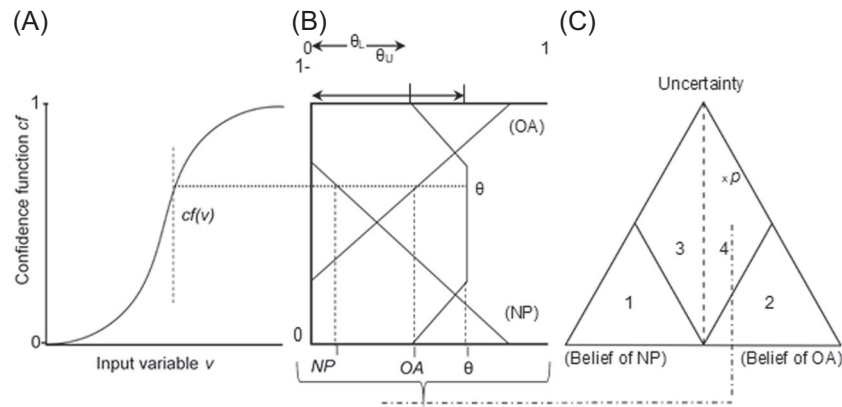
First, principal component analysis was performed on the time-normalized biomechanical waveforms of nonpathological individuals and patients with hip OA. This multivariate technique objectively defines features of variation from temporal waveforms, and is combined with a classification method based on Dempster Shafer Theory of evidence.<sup>25</sup> Pelvis, hip, knee, and ankle kinematics, and hip, knee, and ankle kinetics in all three planes, alongside the three components of the ground reaction force were selected for analysis. The first three principal components of each waveform were selected for the next stage of analysis, resulting in 72 discrete variables per subject.

### 2.7.2 | Data reduction, raking, and selection of input features

The present study makes improvements on previously published feature-selection methods before the application of the Cardiff Classifier,<sup>23</sup> to reduce the risk of over-fitting. The training data were split into two halves and the classifier was used to rank the input features within both datasets rendering the top 19 most robustly discriminatory input features for classification (Appendix 2). During the feature selection stage, the data was split into two halves and the classification procedure was followed using every variable within the training dataset. For each input feature, all the subjects were classified using the feature, and a classification accuracy was determined. This was repeated for each half, and the average classification accuracy across the two sets was used to rank the input features. The target number of retained features was 18, based on previous work in a knee OA cohort,<sup>26</sup> however the 18th and 19th ranked features had the same average classification accuracy and hence 19 input features were selected (Appendix 2).

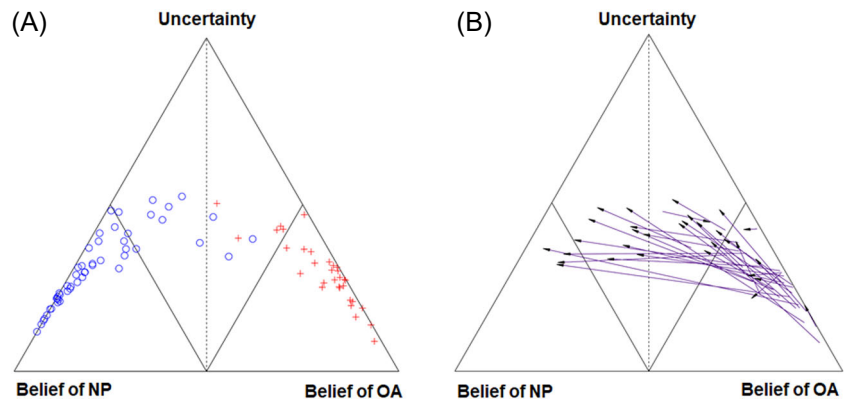
### 2.7.3 | Data classification

Cardiff Classifier was “trained” to discriminate gait characteristics of the 32 included patients with hip OA from that of the 25 non-pathological individuals. The gait characteristics of each individual subject was described using the 19 selected biomechanical features from the previous step. This training process defines the control



**FIGURE 2** The classification method showing the interaction of its three main stages. (A) Conversion of input variable,  $v$ , into confidence factor  $cf(v)$  using the sigmoid confidence function. (B) Conversion of confidence factor into body of evidence (BOE). Linear relationships between confidence factor and belief functions (Non-Pathologic [NP], Osteoarthritis [OA], and Uncertainty [ $\theta$ ]) (solid lines) are constructed using a predefined upper ( $\theta_U$ ) and lower ( $\theta_L$ ) boundary of uncertainty. The point at which the value of the confidence factor (dotted line) intersects these lines gives the three corresponding belief values (dashed line), Belief of NP, Belief of OA, and Uncertainty, which make up the BOE. (C) The visualization of the BOE within a simplex plot, denoted by the point  $p$ . The three belief values are plotted as a distance towards the corresponding vertex (NP), (OA), and  $\theta$ . The simplex plot is divided into four regions: 1 denotes the dominant NP classification region, where  $B(NP) \geq 0.5$ ; 2 denotes the dominant OA classification region where  $B(OA) \geq 0.5$ ; 3 denotes the nondominant NP classification region, where  $0.5 > B(NP) > B(OA)$ , and 4 denotes the nondominant OA classification regions, where  $0.5 > B(OA) > B(NP)$ . The dotted vertical line, along which  $B(OA) = B(NP)$ , is the decision boundary between a classification of NP and OA gait characteristics

**FIGURE 3** (A) Simplex plot of the classification of the 25 nonpathological (NP) individuals (50 individual legs represented by blue circles) and 32 individuals with hip osteoarthritis (OA) (32 affected legs, represented by red crosses) which were used to train the Cardiff Classifier on the biomechanical features of severe osteoarthritic gait. (B) Recovery of gait function in 32 individuals with hip OA at 1 year after total hip arthroplasty



parameters of the sigmoid curve, termed the Confidence Function, which converts each biomechanical feature (principal component value) for each individual into a value between 0 and 1. These values are then converted into a body of evidence: (Belief of Non-Pathologic, Belief of OA, and Uncertainty) through the assignment of upper and lower boundaries of probability. The threshold used to categorize Belief of OA was  $\geq 0.5$  and determined dominant Belief of OA. Finally, evidence is combined for a single individual using Dempster's rule of combination, resulting in a single combined body of evidence for each individual. As the sum of all three belief values (continuous probabilities) equate to 1 (or 100%), they can be easily visualized using a simplex plot, also known as a ternary diagram (Figures 2C and 3). The robustness of the classification was validated using leave-one-out cross validation, in which  $n-1$  subjects are used to train the classifier, which is then tested on the one left out subject. This process is repeated  $n$  times until each subject has been left out.

The trained classifier was then used to calculate the three belief values; Belief of OA, Belief of Non-Pathologic, and Uncertainty (which are presented as continuous data in decimal form, ranging from 0 to 1). For this study, the objective change in gait function was defined as the difference between the pre- and postoperative Belief of OA values. Henceforth, change in Belief of OA is denoted as change in *overall gait function*.

## 2.8 | Statistical analysis

Statistical analyses were performed using MATLAB R2016b and IBM SPSS Statistics version 26. A  $p$  value below .05 was considered statistically significant. Sample size was estimated on other outcome variables published previously.<sup>27</sup> Normality of data were assessed using Shapiro-Wilk tests and Q-Q plots. To investigate whether

**TABLE 2** Evaluation of function in individuals with hip osteoarthritis before and 12 months after total hip arthroplasty (THA)

Cardiff Classifier gait function (Belief values <sup>a</sup> )	Mean (SD)		Difference between pre- and postoperative assessment <i>p</i> value
	Preoperative function within 1 month before THA <i>n</i> = 32	Postoperative function 12 months post THA <i>n</i> = 32	
Belief of Osteoarthritis	0.68 (13)	0.36 (20)	<.001
Belief of Non-Pathologic	0.05 (5)	0.26 (18)	<.001
Uncertainty	0.27 (9)	0.39 (8)	<.001
Time and distance parameters <sup>b</sup>			
Gait speed (m/s)	1.1 (0.2)	1.2 (0.2)	<.001
Normalized gait speed	0.36 (0.06)	0.40 (0.06)	<.001
Stride length (m)	1.1 (0.13)	1.2 (0.12)	<.001
Patient-reported outcome measures (HOOS) <sup>b</sup>			
Symptoms	40 (15)	83 (14)	<.001
Pain	45 (13)	87 (13)	<.001
Activities of daily living	50 (14)	87 (13)	<.001
Sport and recreation	25 (17)	71 (22)	<.001
Hip-related quality of life	28 (15)	72 (17)	<.001
Performance-based functional tests <sup>b</sup>			
Timed up and go test, seconds	12.4 (1.8)	10.9 (1.6)	<.001
Five times sit-to-stand test, seconds	14.9 (4.4)	11.8 (3.1)	.002
Single limb mini squat test, repetitions/30 s	19.9 (7.8)	25.1 (8.9)	.001

Abbreviation: HOOS, Hip Disability and Osteoarthritis Outcome Score.

<sup>a</sup>The sum of all three Belief values equate to 1.

<sup>b</sup>These data have previously been published elsewhere (27) and are included in the present study for original analyses related to a novel research question.

preoperative gait function could predict improvements in patient-reported function and gait function after THA multivariable linear regressions were performed. Age and BMI were included in the regression model as these factors are reported to impact walking speed.<sup>37</sup> Linear correlations (Pearson's correlation coefficient) were used to explore potential relationships between change in overall gait function and change in patient-reported and performance-based function after THA. Correlations were interpreted according to Dancey and Reidy; an *r* value of  $\pm 1$  interpreted as a perfect correlation,  $\pm 0.7$ – $\pm 0.9$  strong,  $\pm 0.4$ – $\pm 0.6$  moderate,  $\pm 0.1$ – $\pm 0.3$  weak and 0 inferring no correlation.<sup>38</sup>

Sample size calculations were made a priori for a different study aiming to evaluate the degree of pre- to postoperative change in Gait Deviation Index.<sup>27</sup> Sample size calculation of the original study was performed to detect a difference of 5 GDI units between patients with hip OA and healthy controls. With the power set at 0.8, 24 subjects were needed in the hip OA group.<sup>27</sup>

### 3 | RESULTS

Out of the 40 patients with hip OA, six received a THA with a posterior approach, and two had incomplete 3D gait data, rendering a total study sample of 32 patients with complete pre- and 1-year postoperative assessments that were included in this study (Figure 1). The excluded individuals with hip OA did not differ from the studied OA group with regards to age, weight, BMI, or years with symptomatic hip OA.

#### 3.1 | Classification of preoperative gait function and change after surgery

The trained classifier had an accuracy of 96.4% (using leave one out cross-validation) in distinguishing between gait patterns of individuals with hip OA and nonpathological individuals (Figure 3A). Overall gait

**TABLE 3** Multivariable linear regressions for postoperative change in patient-reported function (HOOS-ADL) and gait function by means of Cardiff Classifier, respectively

Model/explanatory variable	R <sup>2</sup>	Adjusted R <sup>2</sup>	Model p value	Unstandardized β	Standardized β	Explanatory variable p value	95% CI
Change in HOOS ADL	.35	.28	.01				[32.0, 195.9]
Preoperative gait function				52.45	.37	.02	[8.5, 96.4]
Age				-.93	-.47	.01	[-1.6, -0.2]
BMI				-1.87	-.39	.03	[-3.5, -0.2]
Change in gait function	.30	.23	.02				[-1.9, -0.1]
Preoperative gait function				-.56	-.37	.08	[-1.1, -0.1]
Age				.01	.44	.02	[0.0, 0.0]
BMI				.02	.32	.08	[0.0, 0.0]

Note: β, Coefficient beta.

Abbreviations: BMI, body mass index; CI, confidence interval; HOOS-ADL, hip disability and osteoarthritis outcome activities of daily living subscale.

**TABLE 4** Linear correlations between change in gait function as measured by Cardiff Classifier Belief of Osteoarthritis and change in patient-reported- and performance-based function after total hip arthroplasty

Change in patient-reported outcome measures (HOOS)	Change in gait function	
	r	p
Pain	-.64	.000
Symptoms	-.69	.000
Activities of daily living	-.60	.000
Sport and recreation	-.49	.005
Hip-related quality of life	-.52	.002
Change in performance-based functional tests		
Timed up and go test	.34	.06
Five times sit-to-stand test	.21	.26
Single limb mini squat test	-.24	.19

Note: The correlation is significant at the level of .01 (2-tailed).

Abbreviation: HOOS, Hip Disability and Osteoarthritis Outcome Score.

function improved significantly, as indicated by a reduction in the Belief of OA value from 0.68 to 0.36, and the Belief of Non-Pathologic value increased from 0.05 to 0.26 at 1 year after surgery (Table 2).

### 3.2 | Predictive value of preoperative gait function

Preoperative gait function, quantified and summarized using Cardiff Classifier, in combination with age and BMI at baseline explained 35% of the total variance in the change in patient-reported Activities of Daily Living subscale of HOOS (Table 3). Preoperative gait function, age and BMI at baseline explained 30% of the total variance in

change in gait function after THA (i.e., a reduction in Belief of OA) (Table 3).

### 3.3 | Relationship between change in gait function and change in patient-reported and performance-based function

Moderate to strong negative correlations were found between change in gait function and change in all subscales of HOOS (i.e., a reduction in Belief of OA indicative of reduced gait pattern deviations, and increase in HOOS subscale scores indicative of improved patient-reported outcome) (Table 4). On the contrary, no correlations were found between change in gait function and change in any of the three performance-based functional tests (Table 4).

## 4 | DISCUSSION

This study investigated whether preoperative gait function, quantified and summarized by means of the novel Cardiff Classifier, could predict improvements in patient-reported function, and gait function 1 year after THA. Results showed that preoperative gait function, together with age and BMI, predicted more than a third of the total variance of improvements in patient-reported activities of daily living (35%), as well as improvements in gait function after surgery (30%). Thus, preoperative overall gait function is associated with postoperative patient-perceived outcomes, as well as with objectively assessed postoperative gait function. Moreover, improvements in gait function were also strongly associated with improvements in patient-reported hip-related symptoms and pain, moderately associated to patient-reported function, however, not to improvements in performance-based function. These findings suggest that improvements in gait function after surgery are more closely related to how

patients self-report function and pain, rather than their maximal performance of functional tasks of various sorts.

To the best of our knowledge, this is the first study reporting results of Cardiff Classifier among patients with hip OA, while in previous literature it has been successfully applied in patients with knee OA.<sup>23,25,26,39</sup> In the present study, the trained classifier had an accuracy of 96.4% in distinguishing between hip OA and non-pathological individuals, demonstrating that this approach is applicable also in this group of patients. In patients with knee OA, accuracy of the classifier ranged between 90% and 94%.<sup>25</sup> The Belief of OA value was significantly reduced from 0.68 to 0.36 at the 1-year follow-up (Table 2), indicating that overall gait function improved significantly following THA. However, gait pattern deficits still persisted after surgery (Figure 2). These findings are in line with a recent meta-analysis investigating biomechanical changes and recovery of gait function after THA, in which it was reported that although selected gait parameters appeared to normalize in comparison to healthy individuals, residual deficits in sagittal plane hip range of motion, walking speed, and stride length were present at 1 year after surgery.<sup>40</sup>

A comprehensive gait index, such as the Cardiff Classifier or the Gait Deviation Index, objectively describes modes of variation across the entire gait cycle, accounting for highly correlated features, such as peaks, range of motion, and loading rate within a single component,<sup>41–43</sup> which may be viewed as a key advantage over selecting and reporting discrete gait metrics. Both indices are two-stage techniques which can briefly be summarized as (i) a reduced-order approximation of gait data is determined using matrix factorization, resulting in a smaller set of multivariate gait “features” (ii) individual or group differences in “scores” for these features are mathematically summarized. It is the latter step in which the methods deviate significantly, with the Gait Deviation Index calculating the scaled distance of each new subject from a control group. The Cardiff Classifier approach, by comparison, trains a Dempster Shafer Theory classifier, a mathematical framework for combining evidence with associated uncertainty, to discriminate between healthy and pathological (typically preoperative) function. Changes following intervention are thus typically defined as a reduction in the Classifier belief that the subject belongs to the pathological group. However, a reduced Belief of OA does not necessitate an increased Belief of Non-Pathologic, but rather, less certainty of an “OA” classification.

In contrast to the Gait Deviation Index where a predefined set of variables constitute the comprehensive index, irrespectively of the patient group or gait deviations, the Belief values of the Cardiff Classifier entails raking and selection of input features, i.e., sorting out the most discriminatory variables based on the current dataset. In the present study, the three most robustly discriminatory gait features included reduced sagittal plane range of motion in the hip and pelvis throughout the gait cycle, and reduced knee flexion and extension moment peaks (Appendix 2). In patients with knee OA, the corresponding gait features included reduced vertical and anterior-posterior peak ground reaction forces, and avoidance of knee extension moment.<sup>44</sup> Whether or not a different cohort of patients with

hip OA would display similar or the same discriminatory gait features remains to be answered. However, the most discriminatory gait features are in accordance with previous studies evaluating gait patterns in patients with hip OA and THA, reporting reduced sagittal and frontal plane kinematics,<sup>6,14,45,46</sup> and altered gait to increase medio-lateral stability in an effort to diminish the demand on the hip abductors.<sup>47</sup> Knowing that the most discriminatory gait features are in line with previous research may be viewed as a strength, i.e. a “concurrent validation” of the features included in the Classifier. These results implicate that the Belief values (Figure 3) could be used for monitoring change over time, and to quantify potential changes following interventions. It should be noted, however, that the Classifier is only sensitive to the biomechanical features found to discriminate between nonpathological and preoperative function. As such, biomechanical deviations could exist which are pertinent to postoperative recovery, but are not observed in the preoperative cohort. This is an area for future research.

Two of the performance-based tests used in the present study (the Five Times Sit-to-Stand test and Single Limb Mini Squat test) evaluate time to perform a given task at maximal speed or maximal performance during a specific time frame. In context of the World Health Organization's framework International Classification of Functioning, Disability and Health,<sup>48</sup> it may be argued that these tests reflect *capacity* to perform these specific tasks. Contrary to the third performance-based test used within this study, the Timed Up and Go test, which was carried out at self-selected speed, i.e., “usual” performance. Correspondingly, the 3D gait analysis was also conducted at self-selected speed, thus, reflecting *ability* to perform these activities. In the patient-reported outcome measure (HOOS) used within the present study, patients are asked to rate their perceived difficulties, symptoms or pain while performing a variety of activities where the majority of these activities represent everyday performance and not maximal capacity. This distinction between *ability* and *capacity*, and intensity of the activity, may explain the moderate to strong correlations found between change in gait function and all subscales of HOOS, and the non-existing association between change in gait function and performance-based function. Expressed in other words, quality of movement may hold more significance to patients' perception of improvement than performance-based functional measures which consider only the time taken or repetitions performed during functional activities.<sup>26</sup>

The Osteoarthritis Research Society International provide expert recommendations on the use of patient-reported outcome measures and a core set of performance-based outcomes in clinical trials,<sup>12</sup> as these measures represents different constructs (domains) and thereby complement each other. Based upon current findings, the Cardiff Classifier as a measure of gait ability might improve the understanding of potential synergy between patients perceived physical function and objectively measured overall gait function. However, 3D gait analysis is time consuming, expensive and not easily accessible, limiting its implementation in clinical practice.

Strengths of the present study includes the use of a prospective study design, the use of both clinical and experimental methods to



evaluate function across several measurement construct thereby challenging the use of performance-based tests. Furthermore, this study makes improvements on previously published feature-selection methods before the application of the Cardiff Classifier.<sup>23</sup> There are several limitations to this study which should be acknowledged. The sample size is relatively limited and the heterogeneity restricted as only patients who were able to walk 10 m repeatedly without use of a walking aid, had a BMI below 35, and had not undergone previous lower extremity surgery were considered for inclusion. Therefore, results cannot be generalized to all patients undergoing THA surgery. Within this study, postoperative rehabilitation was not monitored, and postoperative recovery was considered at a single time-point. The trajectories of improvement after surgery may differ depending on what measurement construct is evaluated and outcome measure is being used, specifically during early recovery. Further research of the relationship between trajectories of patient-reported function and objective measures of gait biomechanics is warranted. The use of data reduction and classification techniques introduces the risk of over-fitting, which could over-estimate the accuracy of the classifier's ability to discriminate the biomechanical features related to severe hip OA. Steps were taken to reduce the risk of over-fitting (i.e., data-splitting and cross-validation). In addition, the risk of over-fitting is reduced in comparison to other machine-learning techniques as the control parameters of the transfer function are defined explicitly, as opposed to being iteratively optimized. Finally, it should be noted that 3D gait analysis is a time-consuming and costly method, not available everywhere. The clinical utility of the Cardiff Classifier lies in quantifying impact of disease and treatment on gait patterns to inform healthcare providers and patients on what can be expected in terms of change in overall gait patterns.

## 5 | CONCLUSION

Overall gait function was quantified and summarized using the Cardiff Classifier. The classifier could accurately distinguish between individuals with hip OA and nonpathological individuals demonstrating it to be a useful approach among patients with hip OA. At 1 year after THA surgery, overall gait function was significantly improved, indicated by a reduction in the Belief of OA value. However, gait pattern deficits were still present. Preoperative overall gait function was found to be associated with postoperative patient-perceived outcomes, as well as with postoperative gait function. Improvements in gait function were strongly associated to improvements in patient-reported hip-related symptoms and pain, however, not to improvements in performance-based function. These findings suggest that improvements in overall gait function after surgery are more closely related to how patients self-report function and pain, rather than their maximal performance of functional tasks of various sorts.

## AUTHOR CONTRIBUTIONS

*Conception and design:* Josefine E Naili and Paul Biggs. *Acquisition of data:* Josefine E Naili. *Data analysis and interpretation:* Josefine E Naili,

Paul Biggs, Anders Holsgaard-Larsen, and Cathy A Holt. *Drafting and writing of the article:* Josefine E Naili, Paul Biggs, Anders Holsgaard-Larsen, and Cathy A Holt. All authors have made substantial contributions in the interpretation of data, revising the article critically and all approved of the final version for submission.

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## APPENDIX 1

The mathematical process to calculate a confidence factor, convert it to a set of belief functions and combine the evidence is described below. An example calculation using the data from a subject in a

previous knee osteoarthritis study is given in Beynon M.J. et al, 2006 (Reference No 39).

## Calculation of confidence factor

Each variable is converted into a confidence factor,  $cf(x)$ , between 0 and 1 using a sigmoid transfer function:

$$cf(x) = \frac{1}{1 + e^{-k(x-\theta)}} \quad (1)$$

The value  $\theta$  defines the center of the transfer function, where  $cf(x) = 0.5$ , calculated as the follows:

$$\theta = \mu_{NP} + \mu_{OA} \left( \frac{\sigma_{NP}}{\sigma_{NP} + \sigma_{OA}} \right) \quad (2)$$

Where  $\mu_{NP}$  and  $\mu_{OA}$  are the group means and  $\sigma_{NP}$  and  $\sigma_{OA}$  are the standard deviations for variable  $x$  in the OA and NP groups.

The value  $k$  defines the gradient of the transfer function, and is calculated as follows:

$$k = \frac{l \times \rho(x, y)}{\sigma_x} \quad (3)$$

Where  $l$  is a constant, defined below,  $\rho(x, y)$  is the Pearson correlation coefficient between the variable  $x$ , and the categorical class labels  $y$ , and  $\sigma_x$  is the standard deviation of  $x$  across both groups.

$$l = \frac{n}{\sum_{i=1}^m |\rho_i|} \quad (4)$$

For a dataset of  $n$  subjects,  $m$  is the number of variables in the classification dataset, and  $\rho_i$  is absolute (positive) Pearson correlation coefficient between input variable  $i$ , and the class labels as in Equation 3.

## Conversion of confidence factor to belief functions

The relationship between the three belief functions: belief in OA  $m(OA)$ , belief in NP  $m(NP)$  and belief in uncertainty  $m(\Theta)$ , and the confidence factors following Safranek, Gottschlich (Reference No. 49), where:

$$m(OA) = \frac{B}{1-A} cf(v) - \frac{AB}{1-A} \quad (4)$$

$$m(NP) = \frac{B}{1-A} cf(v) + B \quad (5)$$

$$m(\Theta) = 1 - m(OA) - m(NP) \quad (6)$$

Where  $A$  represents the dependence of the  $m(OA)$  on the confidence factor,  $B$  represents the maximal support which can be assigned to either  $m(OA)$  or  $m(NP)$ . The values of  $A$  and  $B$  should be assigned based on knowledge of the upper  $\Theta_U$ , and lower  $\Theta_L$  boundaries of uncertainty. These were related to upper  $\Theta_U$ , and lower  $\Theta_L$  boundaries of uncertainty as follows:

$$m(\Theta) = 1 - m(OA) - m(NP) = \frac{1 - A - B}{1 - A} \quad (7)$$

$$A = \frac{\Theta_U - \Theta_L}{1 + \Theta_U - 2\Theta_L} \quad (8)$$

$$B = 1 - \Theta_L \quad (9)$$

Within this study,  $\Theta_U = 1$  and  $\Theta_L = 0.8$  were assigned based on previous work on the classification of patients with knee osteoarthritis (Reference No 26).

## Dempster's combination of evidence

For two belief functions  $m_i$  and  $m_j$ :

$$(m_i \oplus m_j)(OA) = \frac{m_i(OA)m_j(OA) + m_j(OA)m_j(\Theta) + m_i(OA)m_j(\Theta)}{1 - K} \quad (10)$$

$$(m_i \oplus m_j)(NP) = \frac{m_i(NP)m_j(NP) + m_j(NP)m_j(\Theta) + m_i(NP)m_j(\Theta)}{1 - K} \quad (11)$$

$$(m_i \oplus m_j)(\Theta) = \frac{m_i(\Theta)m_j(\Theta)}{1 - K} \quad (12)$$

Where  $K$  is the normalisation factor for conflicting probability masses.

$$K = m_i(OA)m_j(NP) + m_j(NP)m_j(OA) \quad (13)$$

Subsequently, by definition:

$$(m_i \oplus m_j)(OA) + (m_i \oplus m_j)(NP) + (m_i \oplus m_j)(\Theta) = 1 \quad (14)$$

OA, Osteoarthritis; NP, Non-Pathologic.

**APPENDIX 2: THE TOP 19 MOST ROBUSTLY DISCRIMINATORY INPUT FEATURES FOR CLASSIFICATION  
(WITH AN AVERAGE ACCURACY >70%)**

Rank	Input feature	Average accuracy (%)	Max (%)	Min (%)	Interpretation
<b>Kinematics</b>					
2	Pelvis tilt angle (PC2)	89.0	95.1	82.9	Reduced sagittal plane ROM throughout gait cycle
4	Pelvis obliquity angle (PC2)	85.4	87.8	82.9	Reduced frontal plane ROM throughout gait cycle
1	Hip flexion angle (PC2)	93.9	95.1	92.7	Reduced sagittal plane ROM throughout gait cycle
6	Hip adduction-abduction angle (PC2)	81.7	85.4	78.1	Reduced hip frontal ROM throughout gait
15	Hip internal rotation angle (PC2)	74.4	82.9	65.8	A relative hip internal rotation at push-off, as opposed to external rotation
9	Knee flexion angle (PC2)	79.3	80.5	78.1	Reduced ROM during stance, reduced peak flexion during swing, early transition to mid-swing
16	Knee flexion angle (PC3)	72.0	73.2	70.7	Similar to PC2 (described above), with a more subtle reduction in ROM throughout stance and swing, delayed peak swing
13	Ankle plantarflexion angle (PC2)	76.8	78.1	75.6	Increased ankle dorsiflexion in mid-stance, reduced plantarflexion at push-off, reduced dorsiflexion during swing phase
14	Ankle inversion angle (PC2)	75.6	78.1	73.2	Reduced frontal plane ROM at the ankle
18	Ankle inversion angle (PC1)	70.7	73.2	68.3	Reduced magnitude of ankle inversion angle throughout stance
<b>Kinetics</b>					
7	Hip flexion moment (PC2)	80.5	90.2	70.7	Reduced hip flexion and extension moment peaks
8	Hip internal rotation moment (PC2)	79.3	85.4	73.2	Greatly reduced early stance external peak, and slightly reduced and prolonged internal moment during mid-late stance.
12	Hip internal rotation moment (PC1)	78.1	78.1	78.1	Greatly reduced internal hip moment peak in late stance
3	Knee flexion moment (PC2)	85.4	87.8	82.9	Reduced knee flexion and extension moment peaks
17	Knee adduction moment (PC1)	72.0	75.6	68.3	Magnitude of the knee adduction moment throughout stance
19	Knee adduction moment (PC2)	70.7	73.2	68.3	Reduced first peak adduction moment in relation to the second peak
<b>Ground reaction force</b>					
5	Anterio-posterior ground reaction force (PC1)	82.9	82.9	82.9	Reduced ground reaction force peaks
10	Medio-lateral ground reaction force (PC3)	79.3	80.5	78.1	Slightly reduced biphasic (double peak) nature of medial ground reaction force, and reduced lateral force peak at loading response
11	Vertical ground reaction force (PC1)	78.1	85.4	70.7	Greatly reduced biphasic nature of vertical ground reaction force, and reduced rate of load acceptance and push of (gradient of the curve at early and late stance)

Abbreviations: PC, principal component; ROM, range of motion.