

Preoperative Ambulatory Measurement of Asymmetric Leg Loading During Sit-to-Stand in Hip Arthroplasty Patients

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Abstract—Total hip arthroplasty (TGA) is a successful surgical procedure to treat patients with hip osteoarthritis. Clinicians use different questionnaires to evaluate these patients. Gait velocity and these questionnaires; usually show significant improvement after TGA. This clinical evaluation does, however, not provide objective, quantifiable information about the movement patterns underlying the functional capacity, which is clinically important and can currently only be obtained in a gait laboratory. There is a need to improve patient instructions and to quantify the rehabilitation process. The sit-to-stand (STS) movement is an objective performance-based task, whose assessment is related with the evaluation of functional recovery. Twenty two patients with hip osteoarthritis participated in this study. For each patient, validated questionnaires were administered and gait velocity was measured. Time, ground reaction forces, and lower limb asymmetry parameters were calculated using the instrumented force shoes (IFS) during STS movement with and without armrest. Significant inter-limb asymmetry was observed. No correlation was found between any parameter and gait velocity and questionnaires outcomes. Significant differences in time and force parameters between with/without armrest were found. Concluding, inter-limb asymmetry can be evaluated with the IFS supplying important additional information not represented by gait velocity and questionnaires usually used.

Index Terms—Gait parameters, ground reaction forces, instrumented force shoes (IFS), inter-limb asymmetry, sit-to-stand (STS), total hip replacement.

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I. INTRODUCTION

THE GOAL for any rehabilitation program after total hip replacement is to maximize the functional status of the patient and to minimize postoperative complications. It is important to evaluate pain, mobility performance, activities of daily living, and overall satisfaction and welfare of the patient after a total hip arthroplasty (THA) compared with the preoperation situation. The present clinical evaluation is not based on objective physical measurements but depends on the subjective opinion of the patient and the therapist. In addition, it does not provide information about the movement patterns underlying the functional capacity. Clinically there is a need for objective biomechanical assessment of mobility performance to quantify objectively and thereby help in the decision support in several phases of treatment and rehabilitation process.

To evaluate mobility performance, activities of daily living, pain, as well as the satisfaction and welfare of the patient, clinicians use several standardized and validated questionnaires [5]–[8]. The most used and relevant questionnaires are the Harris Hip Score (HHS) and Traditional Western Ontario and McMaster Universities osteoarthritis index (WOMAC) [9], [10]. Gait velocity has been measured in several studies as a method to assess the functional capacity in patients with OA [9], [11]. It has been shown that walking ability is positively related to the way in which patients develop a proper role in everyday life [12], [13]. Gait analysis is a useful method for assessing functional deficits before and after THA [14], [15]. The questionnaires mentioned, however, depend on the subjective opinion of the patients, the physiotherapist or clinician and gait velocity, although is an objective and quantitative evaluation method is a very limited way to assess the status of the patient and provide information about the movement patterns underlying the functional capacity, which makes it difficult to perform an accurate and objective assessment [16].

A basic prerequisite for mobility in daily life and a pre-condition for physical independency is rising from a seated to a standing position [17]. Rising from a chair is regarded as one of the most demanding tasks in our daily life [18], and it has been accepted as a prerequisite for successful gait performance [19]. The sit-to-stand (STS) movement has proven to be an objective performance-based task, whose assessment can lead to the evaluation of functional recovery [20], [21]. When weight bearing is symmetrical, each lower limb provides a comparable contribution to the STS movement [22]. However, amongst people with affected hip joint the range

of motion or strength differs between sides. For people with an affected hip joint, the STS movement is a difficult and challenging task [23]. Its performance involves large movement amplitudes and hip and knee muscles need to generate sufficient power to lift the body mass [24]. In patients with OA, asymmetric limb loading appears to be present while they perform STS movements, with significant differences between patients and controls [20], [21].

Upper extremity assistance is also a common compensation during the STS task [25]. Some individuals are unable to rise from a chair without using the armrests, which decreases the force required by the lower extremities and/or provides stability [26].

Consequently, there is a clinical need for objective physical measurements to evaluate the force distribution on both legs with and without armrests in patients with OA. Objective functional mobility analysis can currently only be performed in a specialized and dedicated gait laboratory not generally available for clinical assessment in orthopedic practice [2], [3], [27]. Emed and Pedar systems can be used to measure plantar pressure during static and dynamic activities. This tool allows us to better meet the biomechanical behavior of the foot but there are several factors that can lead to errors of interpretation. The technological complexity of these systems, their accuracy, repeatability, and reliability, have been widely studied. The results found show significant errors in the temporal measurement, being inadequate especially in the detection of start and end support time [27], [28]. It will, therefore, be necessary to go further into these systems to measure the ground reaction forces (GRF) with precision and scientific rigor. On the other hand, these measurement systems only give us information about the vertical GRF. A new ambulatory measurement system opens new perspectives to evaluate asymmetric limb loading in patients with OA. Ground reaction forces provide indirect information about internal joint loading [30]. Ground reaction forces have been used to quantify atypical limb loading for individuals before and after hip arthroplasty [31], [32]. Instrumented force shoes (IFS) are suitable for the measurement of GRF during different tasks [32]–[36].

Previous studies with the IFS have focused on gait analysis. Schepers *et al.* and van den Noort *et al.* have demonstrated that IFS are suitable for the measurement of ground reaction forces during walking in stroke and OA patients [35]–[37]. However, evaluation of STS movement with IFS has not yet been studied.

A meta-analysis of Vissers *et al.*, 2011 has shown that gait velocity and outcome of the HHS and WOMAC questionnaires demonstrate significant changes when comparing pre- to post-operative conditions [16].

The purpose of the present study is twofold. First, to evaluate if the IFS are able to quantify objectively and provide relevant information about the mobility performance of the patients with OA before THA in an outpatient clinical setting, complementary to gait velocity and questionnaires already used in clinical practice. Second, to investigate whether the IFS is a sufficiently sensitive instrument for quantitative assessment of asymmetry during STS movements of patients with OA and/or for revealing differences between the STS movement with and without arm support.

II. MATERIALS AND METHODS

A. Subjects

Twenty two patients with hip OA participated in this study (10 females and 12 males, age: mean 63(10)(mean(SD)) years, body mass 84.3(11.2) kg and height 1.63(0.34) m). Twelve patients completed the task without using the armrest (age: 60.8(9.2) years (mean(SD)), body mass 84.5(9.0) kg and height 1.73(0.08) m) and 10 patients completed the task with using the armrest (age: 66.5(9.7) years, body mass 84.1(14.0) kg and height 1.52(0.49) m)

Patients with OA that had been selected to undergo a primary THA were recruited from Medisch Spectrum Twente (Enschede, The Netherlands). The inclusion criteria were age between 50 and 80 years, primary unilateral OA of the hip and a THA planned within the next four months. The exclusion criteria were a contralateral THA, any kind of leg arthroplasties, rheumatoid arthritis, any neurological disorder, other degenerative diseases, revision/reoperations of primary hip prosthesis planned or the inability to understand instructions or the questionnaire.

The study protocol was approved by the Medical Ethics Committee (METC) of the Medisch Spectrum Twente, (Enschede, The Netherlands) and full written consent was obtained from all participants.

B. Data Collection Procedures

The measurement sessions were performed in the Department of Orthopedic Surgery at the Medisch Spectrum Twente. Subjects were seated in a chair with armrests. The chair height and depth were adjusted in a way that the knee angles were 90° in a sitting position. The subjects' ankles were placed vertically under the knee. The subjects were asked to look straight forward and to rise at their own preferred speed with their arms folded across the chest after the "1, 2, 3, and rise" command. The subjects were instructed to stand quietly in the anatomical position for 5 s after each trial [37]. The placement on the seat and the position of the feet were marked to guarantee the same starting position in every trial. It was tested whether the subjects were able to stand up without using the armrests before the trial. If the subject was not able to perform the trial without using the armrests, he/she was allowed to use his/her arms. Three successful trials were collected per subject.

In addition, to be able to answer the first research question, subjects were instructed to walk repeatedly at their preferred speed through a corridor between a predefined start and end point, 10 m. apart at a constant speed. The gait velocity was calculated measuring the time required to walk the distance of 10 m using a stopwatch and a measuring tape. The stopwatch was started as soon as the subject's foot crossed the start line and recording was stopped when the person's second foot crossed the finish line. Three successful trials were collected per subject. The average gait velocity for all trials was calculated from distance walked and walking time (gait velocity (GV)= distance/time).

Questionnaires: Subjects were asked, with the researcher's supervision, to complete two validated questionnaires to evaluate hip function in THA patients: the Dutch version of the HHS [7], and the WOMAC [9], [10].



Fig. 1. IFS (right shoe). Each force shoe (left and right) has two sensors modules: one under the forefoot and one under the heel. Sensor module includes a force/torque sensor and a motion tracker.

C. Instrumentation

The ambulatory measurement system used in this study consisted of an IFS (Xsens Technologies B.V., Enschede, The Netherlands) for 3-D measurement of forces and torques under the feet, as well as 3-D kinematics of the feet. The complete measurement system was built in a shoe sole allowing complete freedom of movement. The measured data was sent wirelessly to a PC or laptop, via an on-body hub (Xbus master). The IFS (Fig. 1) is adjustable for shoe size. The IFS signals were sampled at 50 Hz.

These IFS have been validated and used before successfully in different studies [35], [37], [40]. It has been demonstrated that the IFS provide reliable accurate measurements of 3-D ground reaction force, position and orientation [38]. Moreover, Van den Noort JC *et al.* have demonstrated that IFS are suitable for the measurement of ground reaction forces in patient with OA [36], [37]. The measurement system was calibrated using Faber *et al.* method before the measurement sessions [41].

D. Data Analysis

The following IFS parameters were determined for the STS with using the armrest and without using the armrest separately. The parameters were calculated for both involved and uninvolved legs. Ground reaction forces were normalized to body weight (%BW).

Time Parameters: The STS maneuver was considered to start at T_{start} , when there was a 5% of body weight (BW) decrease in vertical GRF (vGRF) and to finish (T_{end}) when vGRF stayed within 5% of BW during 0.25 s. The STS duration T_{STS} was defined as $T_{STS} = T_{end} - T_{start}$. The rise time T_{rise} was defined as $T_{rise} = T_2 - T_1$, with, T_1 being the time at which vGRF first exceeds the initial vGRF level measured while the patient was sitting, and T_2 being the time when vGRF reaches body weight for the first time before attaining its maximum value (Fig. 2).

Ground Reaction Force Parameters: Maximum peak of GRF was calculated for vertical ($F_{vGRF,max}$), antero-posterior ($F_{aGRF,max}$) and medio-lateral ($F_{mGRF,max}$) directions, average GRF during quiet standing after STS was calculated for vertical ($F_{vGRF,qs}$), antero-posterior ($F_{aGRF,qs}$) and medio-lateral ($F_{mGRF,qs}$) directions, the dynamic area defined as the area under the vGRF during rise time from T_1 to T_2 ($A_{vGRF,rise}$).

Symmetry Indexes (Involved/Uninvolved) (SI): The symmetry index was calculated using

$$SI = \frac{(V_I - V_U)}{V_U} * 100\% \quad (1)$$

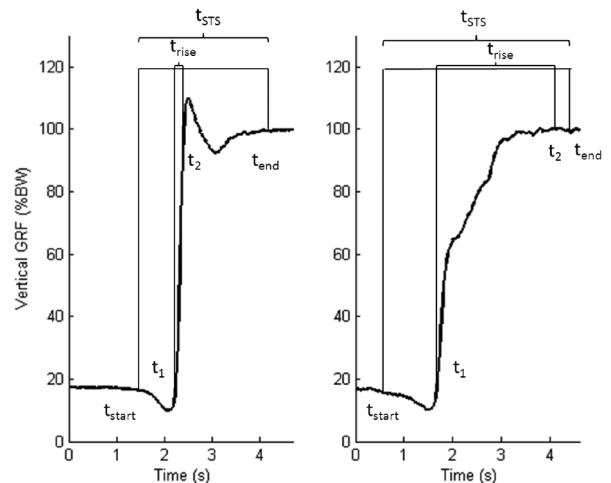


Fig. 2. Time parameters: the sum of the vertical ground reaction forces of left and right limbs are shown for two patients without (left part) and with (right part) using the armrest. STS time and rise time were determined from vGRF. Abbreviations: tSTS, STS time and trise, rise time.

where V_U and V_I are any of the aforementioned parameters for the uninvolved and involved leg, respectively. Perfect symmetry results in $SI = 0 (V_U = V_I)$; positive and negative values indicate a greater asymmetry towards the involved and uninvolved limb, respectively.

E. Statistical Analysis

Simple linear regression analysis using Pearson's correlation coefficients (r) was performed taking the temporal, kinetic and symmetry parameters derived from IFS measurements, as dependent variables, and the gait velocity and the questionnaires outcomes as regressors. Statistical significance was determined as a p-value of less than 0.05. When the standard assumptions for a linear regression were not satisfied a Spearman Rank Order Correlation was performed.

A 95% confidence intervals (C.I.) for the mean of each symmetry parameter were calculated to test if the mean of the symmetry parameters estimated were different to zero. The distribution of the data was summarized and presented in boxplot format.

To investigate whether the IFS are sufficiently sensitive to differentiate between both STS performance, with and without using the armrest, we used the two-sample T-test to test differences in the means of each parameter defined above between the UA and WOUA groups. Statistical significance was determined as a p-value of less than 0.0034. We used a simple Bonferroni correction for multiple comparisons.

III. RESULTS

The mean and standard deviation of the parameters for each patient were determined using the data of the three trials.

Mean and standard deviation of the GRF components of involved and uninvolved limbs of both groups of patients with using the armrest and without using the armrest are shown in the Fig. 3.

Gait Velocity and Questionnaires Outcomes: Mean and standard deviation (SD) of gait velocity was calculated for both

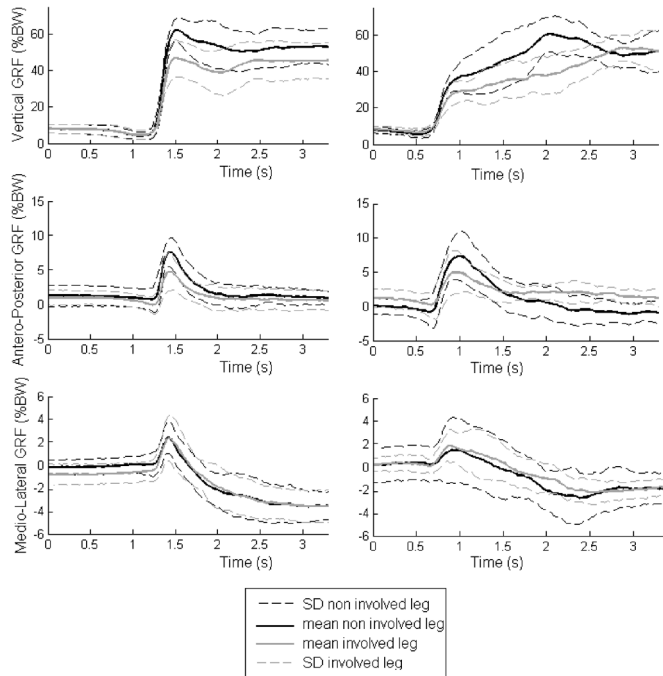


Fig. 3. Ground reaction forces: mean and SD of the vertical, antero-posterior and medio-lateral ground reaction force for involved and uninvolved limbs separately of both groups of patients without (A) and with (B) using the armrest.

groups of patients, with and without armrest, separately. The scores for the group that performed the STS using the armrest and without the armrest were 0.72(0.19) and 0.99(0.24), respectively.

Mean and standard deviation for WOMAC pain, WOMAC stiffness, and WOMAC physical function outcomes were calculated for both groups of patients, with and without armrest, separately. The scores for the group that performed the STS using the armrest were 11.69(3.13), 5.20(2.04), and 39.13(14.75), respectively. The scores for the group that performed the STS without using the armrest were 9.85(2.38), 4.67(1.87), and 33.86(9.6), respectively. HHS scores were, 46.70(11.74) and 56.08(17.14) for the group that performed the STS with and without armrest, respectively. There were no significant differences in any questionnaires outcomes between both groups.

Symmetry Indexes: Boxplots of the SI of the vGRF parameters without and with using the armrest are plotted in Fig. 4.

Mean, SD, and C.I. of the symmetry indexes for the STS task with and without using the armrest are shown in Table I.

The SI of $F_{vGRF,max}$ parameter was significantly different from zero for both groups, using the armrest ($P = 0.041$) and without the armrest ($P = 0.003$). The SI of $A_{vGRF,rise}$ was significantly different from zero for the group that performed the STS without using the armrest ($P = 0.005$). There was no significant asymmetry in $F_{vGRF,qs}$.

The SI of $F_{aGRF,max}$ parameter was significantly different from zero for the group that performed the STS test using the armrest ($P = 0.005$). The SI of $F_{aGRF,qs}$ was significantly different from zero only for the group that developed the STS test without the armrest ($P = 0.018$). There was no significant asymmetry in the medio-lateral GRF parameters. As can

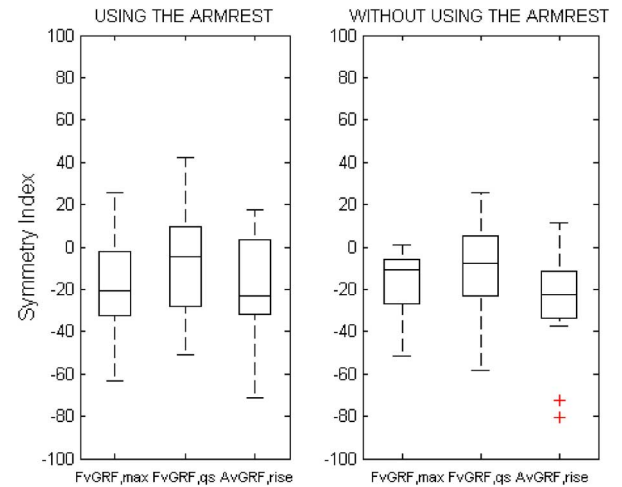


Fig. 4. Boxplot of symmetry indexes of vertical ground reaction force parameters for the group that performed the STS task with and without using the armrest. The box indicates the lower and upper quartiles with the central line showing the median. The top and bottom lines of the box represent, respectively, the medians for the upper and lower halves of the data and the “cat’s whiskers” represent the highest and lowest values of the distribution, excluding outliers (+).

be seen in Fig. 4, boxplots show a large variability of symmetry parameters.

Correlation With Gait Velocity and Questionnaires: No correlation was found between any of the variables studied for both involved and uninvolved limbs for both groups with/without armrest and the GV outcomes. No correlation was found between any of the variables studied for both involved and uninvolved limbs for both groups with/without armrest and the questionnaires outcomes.

Sensitivity of the IFS: Boxplots of the T_{STS} and T_{rise} with and without using the armrest are plotted in Fig. 5. The group that performed the STS task without using the armrest showed significant ($P = 6.45 \cdot 10^{-7}$) lower T_{rise} than the group with using the armrest.

The time required to complete the STS task, T_{STS} , was not significantly different comparing with and without using the armrest ($P = 0.058$). Table II shows the comparison between the two difference ways to perform the STS tasks for each GRF parameter calculated with the IFS.

$A_{vGRF,rise}$ for involved and uninvolved vGRF were significantly lower ($P = 1.99 \cdot 10^{-6}$, $P = 4.00 \cdot 10^{-6}$, respectively) for the group that performed the STS without using the armrest than the values of the group that performed the STS using the armrest.

There were no significant differences between both groups in the antero-posterior and medio-lateral GRF parameters.

IV. DISCUSSION

This study demonstrates that inter-limb asymmetry can be evaluated with the IFS irrespective of upper limb assistance using the armrest. T_{rise} and $A_{vGRF,rise}$ showed significant differences between with/without arm support. Moreover, the negative SI of GRF parameters indicates greater asymmetry towards the uninvolved leg, which means that patients put more weight on the non-affected leg throughout the STS movement.

TABLE I
MEAN, SD, AND C.I. OF THE SYMMETRY PARAMETERS DURING STS TASK WITH AND WITHOUT USING THE ARMREST IN SUBJECTS WITH HIP OSTEOARTHRITIS

	Using the armrest		Without using the armrest	
	Mean(SD)	C. I.	Mean(SD)	C. I.
Vertical				
$F_{vGRF,max}$	-18.46±23.24	[-35.98,-093] †	-16.32±14.19	[-25.73,-6.90] †
$F_{vGRF,qs}$	-6.97±27.10	[-27.40,13.46]	-9.40±22.19	[-24.12,5.32]
$A_{vGRF,rise}$	-18.62±24.82	[-37.33,0.10]	-26.95±25.82	[-44.09,-9.82] †
Antero-Porterior				
$F_{aGRF,max}$	-16.72±39.97	[-45.31,11.87]	-29.55±29.07	[-48.03,-11.08] †
$F_{aGRF,qs}$	-166.09±180.94	[-295.53,-36.65] †	58.99±226.52	[-84.93,202.91]
Medio-Lateral				
$F_{mGRF,max}$	-19.77±399.62	[-305.65,266.10]	20.59±80.85	[-30.78,71.97]
$F_{mGRF,qs}$	-188.07±342.51	[-433.08,56.95]	28.26±104.62	[-38.22,94.73]

TABLE II
MEAN ±SD OF GRF PARAMETERS MEASURED WITH THE IFS AND DIFFERENCES BETWEEN STS PERFORMANCE WITH AND WITHOUT USING THE ARMREST. ABBREVIATIONS, UA, USING THE ARMREST, WOUA, WITHOUT USING THE ARMREST. † REPRESENTS STATISTICALLY SIGNIFICANT DIFFERENCES ($P \leq 0.0035$)

GRF		Involved limb		Pvalue	Uninvolved limb		Pvalue
		UA	WOUA		UA	WOUA	
V	$F_{vGRF,max}$	49.59±8.69	53.53±7.89	0.27	63.54±9.44	64.87±7.15	0.23
	$F_{vGRF,qs}$	46.97±8.16	46.12±7.37	0.81	52.78±8.19	53.23±6.55	0.71
	$A_{vGRF,rise}$	40.98±20.06	2.87±1.18	$1.99 \cdot 10^{-6}$ †	55.30±28.13	4.43±32.09	$4.00 \cdot 10^{-6}$ †
A-P	$F_{aGRF,max}$	5.48±2.45	5.42±2.5	0.93	7.86±2.00	7.86±1.92	0.82
	$F_{aGRF,qs}$	0.76±2.00	0.83±1.40	0.85	-0.27±1.76	0.86±0.88	0.1
M-L	$F_{mGRF,max}$	2.62±1.47	2.63±1.87	0.68	2.04±1.94	2.64±1.12	0.68
	$F_{mGRF,qs}$	-1.48±0.83	-3.19±1.30	0.03	-2.14±1.57	3.23±1.30	0.03

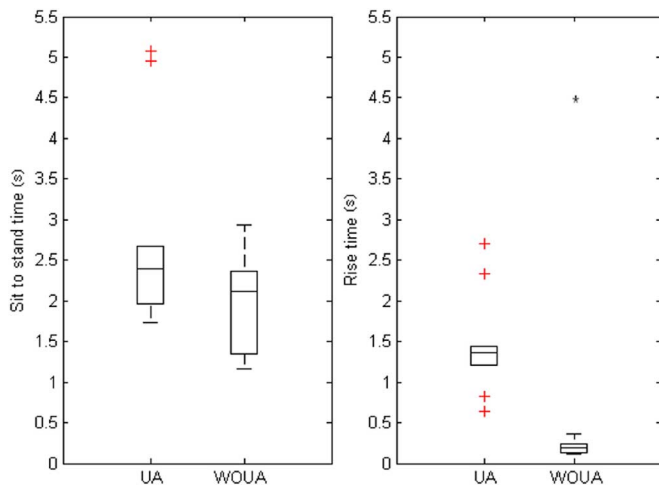


Fig. 5. Boxplot of T_{STS} and T_{rise} for the group that used the armrest (UA) and did not use the armrest (WOUA). * symbol represents significant differences between with/without using the armrest.

The SI, which can be measured with the IFS system in an outpatient setting, provides important additional information about

mobility in these patients which is not represented by gait velocity and questionnaires outcomes.

SI of $F_{vGRF,max}$ during both task modalities, with and without using the armrest, indicates greater asymmetry towards the uninvolved leg during the dynamic STS task. However, during quiet standing after STS we did not find significant weight bearing asymmetry. This indicates an asymmetric pattern during the dynamic balance control of OA patients, putting more weight on the non-affected leg while they are performing the STS task, while the distribution of weight in both, involved and uninvolved limbs, during quiet standing appears to be symmetric in the vertical direction. This preference for the uninvolved side does not depend on upper extremity assistance [26]. This result is comparable with the result of Nederhand *et al.* and van Asseldonk *et al.* in stroke patients that showed dynamic balance control provides more information about the stabilizing mechanism than static weight distribution [42], [43].

Anterior, posterior, medial, and lateral GRF magnitudes are small compared to the vertical GRF, but they could be significant and provide an important contribution to the general performance. Previous studies have shown that normal healthy partic-

ipants demonstrated frontal and transverse displacements and some asymmetries in these planes during rising from a chair [44], [45]. We investigated if there were asymmetries in these directions and how patients with OA developed the STS movement also in these directions.

The negative SI of the $F_{aGRF,max}$ indicates that the values of these parameters are larger for the uninvolved leg for the group that perform the STS without using the armrest. We did not find asymmetries in the maximum antero–posterior GRF for the group that perform the STS using the armrest. Moreover, the negative SI of the $F_{aGRF,qs}$ indicates that the values of these parameters are larger for the uninvolved leg for the group that perform the STS using the armrest. However, the motor control problems that may be exhibited in this asymmetry in bilateral tasks are unclear [42]. Further studies are required to investigate the biomechanical significance of this asymmetry in these kinds of patients.

Bohannon reported that the time for a single STS is informative [46]. Although several studies have reported the time to complete the STS movement [17], [24], [47], there is not an agreement about the duration of one STS transfer in normal subjects. Our results show that the time required to complete the STS task (t_{STS}) is not significantly different if the subject is using his arms or not ($p = 0.06$). However, T_{rise} is significantly lower with using the armrest, as we can see in the Fig. 4. Hence, the time-to-rise (T_{rise}) may be a more sensitive parameter than the total time to perform the STS movement (T_{STS}). This result indicates that the IFS are sufficiently sensitive instrument to differentiate between these two strategies. In addition the $A_{vGRF,rise}$ for both limbs showed significantly larger values using the armrest as compared without using the armrest. This result shows that when the patients perform the STS transition without armrest the movement is faster.

The SI's of all parameters described in the methods section were not correlated with gait velocity. This could indicate that SI provides additional information, which is not represented by gait velocity. Moreover, we did not find a relation between STS parameters and questionnaires outcomes, which supports the findings of Vissers *et al.* and Boonstra *et al.* These questionnaires usually reflect different aspects of functionality and the ability of patients to perform activities, but not how they perform these activities [9]. Patients may try to maintain their functional performance as normal as possible despite the hardship of pain and discomfort. As each technique represents different aspects of the patient's conditions, it is, therefore, important to measure STS parameters in addition to questionnaires and gait velocity, before surgery in order to enable comparison after the operation and tailor rehabilitation programs [20], [48]

One of the limitations of this study is the IFS design. Although the IFSs are found to be suitable for this investigation, the IFS design needs to be optimized for a better adaptation to each patient's feet without the present increment in shoe height and mass [36]. This could be realized through an exact fit of the IFSs for all patients, with different shoe sizes and using a more appropriate choice of sole and insoles materials and smaller and lighter force/moment sensors.

Another limitation of this work was the body mass index of the patients (BMI). The average BMI for the 12 patients who did not use the armrest was 28.2, placing them in the overweight

category according to conventional BMI classification. The average BMI for the 10 patients who did use the armrest was 36.4, placing them in the severely obese or obese-class 2, category. In this case, the difference in BMI between the two groups was not significant and the BMI was not a significant predictor of any of the measured STS variables. Despite this, in future studies, we would recommend to take into account the BMI of each patient. Moreover, although we have shown that the IFS is a sufficiently sensitive instrument for revealing differences between the STS movement with and without arm support, it would have been better to compare both conditions (with/without armrest) for the same patient. In this preliminary study it was not possible because some of the patients could not perform the STS test without the armrest.

In the future, additional studies are required to investigate whether the information found in this study not being represented by gait velocity and questionnaires, is sensitive enough to show differences before and after THA and whether this information is indeed clinically relevant during rehabilitation after THA.

V. CONCLUSION

We conclude that IFS can measure asymmetry and differences in forces when patients with OA perform the STS test with and without using an armrest. Inter-limb asymmetry can be evaluated with the IFS supplying important additional information which is not represented by gait velocity and questionnaires usually used. This makes it a new clinical measurement system, which can be used in an outpatient setting, useful for hip OA patients before a THA. The author(s) declare that they have no competing interests.

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