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Ground reaction forces and external hip joint moments predict *in vivo* hip contact forces during gait

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A R T I C L E I N F O

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A B S T R A C T

Younger patients increasingly receive total hip arthroplasty (THA) as therapy for end-stage osteoarthritis. To maintain the long-term success of THA in such patients, avoiding extremely high hip loads, i.e., *in vivo* hip contact force (HCF), is considered essential. However, *in vivo* HCFs are difficult to determine and their direct measurement is limited to instrumented joint implants. It remains unclear whether external measurements of ground reaction forces (GRFs), a non-invasive, markerless and clinic-friendly measure can estimate *in vivo* HCFs. Using data from eight patients with instrumented hip implants, this study determined whether GRF time series data, alone or combined with other scalar variables such as hip joint moments (HJMs) and lean muscle volume (LMV), could predict the resultant HCF (rHCF) impulse using a functional linear modeling approach. Overall, single GRF time series data did not predict *in vivo* rHCF impulses. However, when GRF time series data were combined with LMV of the gluteus medius or sagittal HJM using a functional linear modeling approach, the *in vivo* rHCF impulse could be predicted from external measures only. Accordingly, this approach can predict *in vivo* rHCF impulses, and thus provide patients with useful insight regarding their gait behavior to avoid hip joint overloading.

1. Introduction

The number of total hip arthroplasty (THA) surgeries is increasing in developed countries (Pabinger et al., 2018; Singh et al., 2019). Such a phenomenon is partially explained by a growing life expectancy (Nemes et al., 2014), as well an increasing number of patients under the 65 years of age seeking THA (Kurtz et al., 2009; Pabinger and Geissler, 2014). The expectations of modern patients often include a return to an active lifestyle (Healy et al., 2008; Hoorntje et al., 2018), which may increase cumulative hip joint loading (Bergmann et al., 2016; Haffer et al., 2021) thereby enhancing joint-bearing surface wear (Battenberg et al., 2013; Schmalzried et al., 2000). Thus, investigating hip joint loads following THA is relevant to guide the expectations of modern patients. However, there is no straightforward means to precisely determine hip joint loads besides *in vivo* contact force measurement using telemetric implants (Bergmann et al., 2001; Damm et al., 2010; Kutzner et al., 2017; Schwachmeyer et al., 2013). Only instrumented THA implants can provide accurate and direct measurement of *in vivo* hip contact forces (HCF) and impulses. The impulse of the resultant HCF (rHCF) may be used to reliably investigate cumulative hip joint loading during daily activities such as gait since joint impulse measurements aggregate the force over the entire duration of the motion cycle (Brisson et al., 2021). Nevertheless, broader implementation of such technologies is not currently feasible.

Use of ground reaction forces (GRFs) as a surrogate measure of HCF could present advantages for clinical use as it is a vector quantity easy to measure using non-invasive and markerless techniques. Several laboratory-based studies have sought to understand functional recovery by monitoring GRF data, as measured by a force platform under the foot (Aqil et al., 2016; McCrory et al., 2001; Wiik et al., 2017), under the assumption that GRF data provide indirect information about hip loading (McCrory et al., 2001). To analyze GRF data, a single or a set of variables (e.g., peak force, loading rate) are commonly selected. However, *a priori* selection of such variables may increase the risk of selection

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bias, which may result in dismissing meaningful information captured by other variables. Additionally, it is not entirely clear whether GRF profiles are always reflective of HCF (Bahl et al., 2020), which introduces additional challenges to the selection of relevant GRF variables. To mitigate these risks, the entire time series data could be analyzed using appropriate statistical methodologies. Yet, a key unanswered question is whether GRF is an appropriate surrogate measure for cumulative hip loading, as measured by the *in vivo* rHCF impulse; and if not, which other relevant variables could help to make the relationship meaningful?

One potential variable that could assist with improving this relationship is the hip lean muscle volume (LMV). Recent investigations in patients with telemetric implants revealed that LMV measures were associated with HCF during gait after THA. Specifically, reduced periarticular LMV contributed to higher *in vivo* HCFs at 3 months and 50 months postoperatively (Damm et al., 2019, 2018); however, the *in vivo* rHCF impulse was not investigated. Furthermore, other biomechanical variables such as external hip joint moments (HJM) have also been used as proxies for HCF, particularly the HJM in the sagittal and frontal planes of motion (Foucher et al., 2009; Giarmatzis et al., 2015; Holder et al., 2020; Wesseling et al., 2015). In fact, gait alterations based on HJMs reductions have been suggested as an effective strategy to reduce HCF in patients with hip pathologies (Foucher et al., 2009; Wesseling et al., 2015) to mitigate persisting mechanical deficits following THA (Beaulieu et al., 2010). Finally, an understanding of the relationship between HJM and HCF has been sought using musculoskeletal modeling to estimate internal HCFs; however, this approach comes with immense time and computational costs, and errors in joint loading estimates that may mislead conclusions on the relationship between external and internal loading variables (Holder et al., 2020).

It remains unclear if surrogate measures such as GRF alone or combined with other measures are strong indicators of the *in vivo* rHCF impulse. Methods based on noninvasive, external measures could enable a broader understanding of hip joint loading across individuals and afford new possibilities for individualized recommendations to avoid hip joint overloading. The aim of this study was to determine the extent to which GRF time series data predicted the *in vivo* rHCF impulse, and whether the addition of other scalar measures (i.e., LMV and HJM) improved model predictions.

2. Methods

2.1. Patients and study design

This study uses an extended dataset of measurements previously reported (Damm et al., 2021, 2019). Data from eight patients ($n = 8$; 2 women, 6 men; mean $\pm$ SD age 61.8 ± 6.2 years) with instrumented hip implants who underwent THA using the direct lateral approach as a treatment for primary hip osteoarthritis were used. At the time of the study, two participants (H2R and H5L) had bilateral hip implants, in which a single implant was equipped with telemetry. No further patient had any other lower limb joint replacements. The study was approved by the institutional ethics committee (EA2/057/09) and registered in the German Clinical Trials Register (DRKS00000563). Patients provided informed written consent before participating in the study. To ensure that the investigated variables were not affected by the acute rehabilitative phase, a dataset from approximately 50 months after THA was used (Wesseling et al., 2018).

2.2. Gait analyses

Gait analyses were performed to determine three-dimensional kinematics and kinetics during barefoot walking at a self-selected speed. Three-dimensional kinematic data were collected with 69 *retro*-reflective markers tracked by an infrared motion capture system operating at 250 Hz (10 MX-S cameras; VICON Nexus version 1.8, VICON, Oxford, UK) using a marker model based on the one previously described by Taylor and colleagues (Taylor et al., 2010). GRFs were sampled at 1000 Hz as patients walked across a floor-embedded force platform (AMTI-BP400600, Watertown, MA, USA). The force platform was located in the middle of a 10-meter walkway, and patients were not informed of its location to prevent them from accelerating/decelerating their gait to target the platform. For a trial to be deemed successful, the ipsilateral foot was required to contact the force platform entirely and cleanly. A minimum of five successful trials were collected per patient within a measurement session. In addition, *in vivo* HCFs were collected synchronously during the gait trials by the instrumented hip implants. A detailed description of the telemetry and its external measurement systems have been previously published elsewhere (Damm et al., 2010; Graichen et al., 2007, 1994). Following data collection, GRF and HCF stance phases were identified as the interval from initial ground contact (zGRF $>$ 20 N) to toe-off (zGRF $<$ 20 N) using an R (version 3.6.1) (R Core Team, 2021) custom script in RStudio IDE (RStudio, Boston, MA, USA). The three GRF components (x: mediolateral; y: anteroposterior; z: vertical; r: resultant) acting on the force platform were calculated with positive forces acting in the lateral, anterior, and superior directions, respectively (Fig. 1). The resultant force (rHCF), which acts on the implant head center (Bergmann et al., 2016), was determined from the three force vectors. To compute external sagittal and frontal plane HJMs, gait data were further processed using commercial software (Visual 3D, C-Motion, Inc., Germantown, MD, USA). A second-order low-pass Butterworth bidirectional filter with 6 Hz cut-off was applied to marker trajectory and force plate data. External HJMs were resolved in a three-dimensional floating axis coordinate system (Wu and Cavanagh, 1995) using inverse dynamics (Winter, 2009). The HJM impulse in the sagittal and frontal planes during the stance phase was calculated using trapezoidal integration of absolute values within the R software environment (R Core Team, 2021). All kinetic data were expressed in non-normalized units, with GRFs in N, rHCF impulses in N $\times$ s, and HJM impulses in Nm $\times$ s.

2.3. Lean gluteus muscle volumes analyses

The LMVs of the ipsilateral gluteus minimus (Gmin), gluteus medius (Gmed), and gluteus maximus (Gmax) muscles were obtained at approximately 50 months post-THA using computed tomography, as shown detailed elsewhere (Damm et al., 2019). Briefly, hip muscle scans were obtained using helical computed tomography with the following parameters: 120 kV, 200mAs, and field of view 40 cm (Toshiba Auilion ONE, V4.61GR004, Tokyo, Japan). After data acquisition, the original scans were reconstructed to 5 mm slice files (GE Medical systems, software version vctl_12.3–2.86, volume viewer, smooth 1 filter). The volumes between the anatomic landmarks of the fourth lumbar vertebrae and the lesser trochanter were measured to control for variability in patient heights. The selected muscle slices were then manually outlined and the intermediate surface was interpolated using dedicated software (Osirix Imaging Software, Geneva, Switzerland; Amira Visage Imaging, Berlin, Germany). Three consecutive slices were considered for analysis by going six slices cranial of the anatomic landmark greater trochanter. To obtain LMVs, the total volume and the muscle fatty degeneration of each muscle were quantified. The latter was assessed using a standardized Hounsfield Unit based approach (Daguet et al., 2011; Engelken et al., 2014). The LMVs were expressed in cm^3.

2.4. Statistical analyses

To perform time series-based analyses, functional data analysis (FDA) was used. The functional linear modeling (FLM) with scalar response framework allows predicting rHCF impulse based on GRF time series data, interpreted as a functional analog of linear regression analysis (Ramsay and Silverman, 2005). Furthermore, FLM allows the integration of additional covariates into the model to understand their

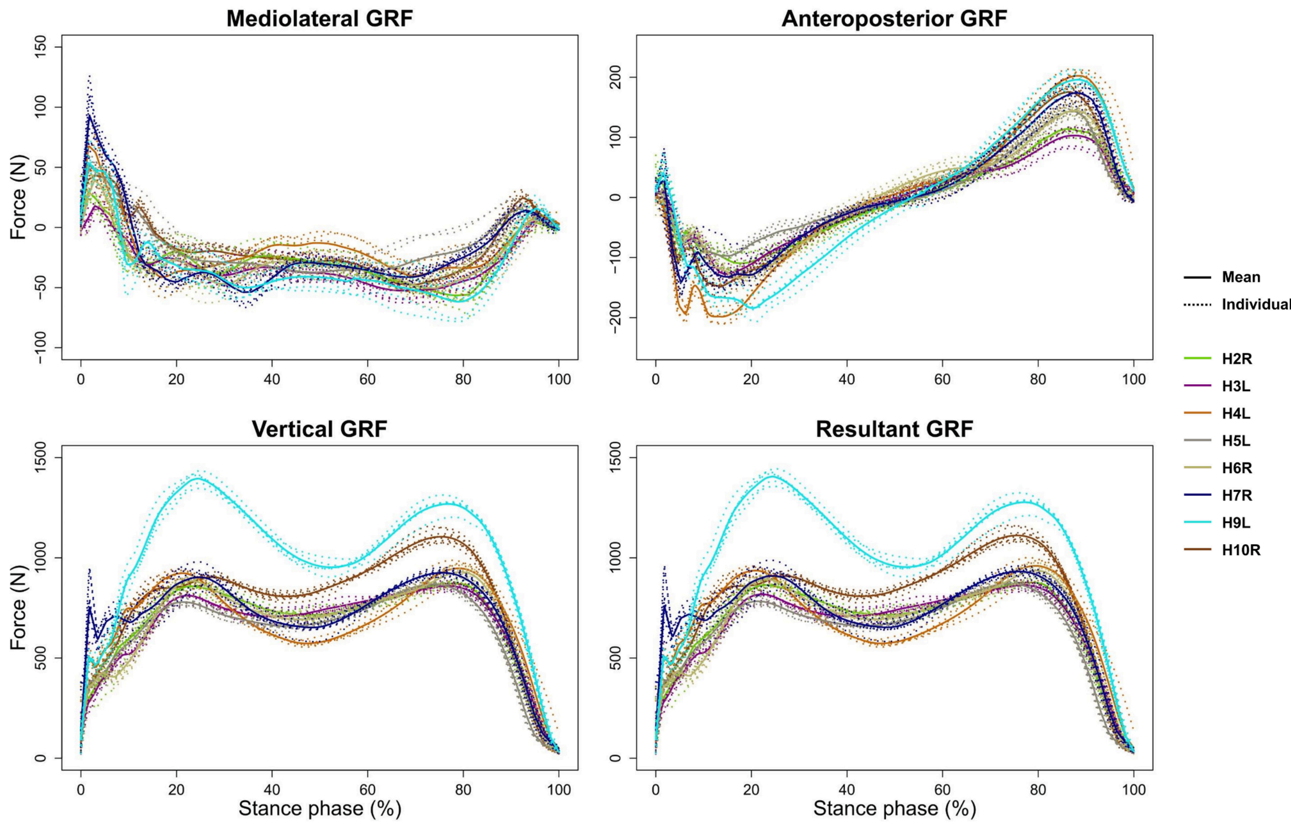

Fig. 1. Individual (dotted lines) and mean (solid lines) waveforms time-normalized to the stance phase for each GRF component (mediolateral, anteroposterior, vertical, and resultant) for all total hip arthroplasty patients with an instrumented hip implant at approximately 50 months after total hip arthroplasty. Positive axis directions are lateral, anterior and superior for the mediolateral, anteroposterior and vertical components, respectively.

influence on the outcome measure. A class of FLMs with scalar response was considered to estimate the rHCF impulse, as shown in Eq. (1).

$$Y_{ij} = a + X_i^T\beta + \int_0^1 f_{ij}(t)\gamma(t)dt + \epsilon_{ij},\ \ \mathrm{E}\epsilon_{ij} = 0, \mathrm{D}\epsilon_{ij} < \infty \tag{1}$$

The Y_{ij} refers to the scalar response (i.e., rHCF impulse). X_i refers to the scalar covariates of patient i and for each step j f_{ij} refers to the functional covariates considered. The scalar covariates were Gmin, Gmed, and Gmax LMV as well as the HJM impulses in the frontal and sagittal planes. The functional covariates were the GRF time series data. Each GRF step was linearly aligned to a common time interval (0, 1) keeping the impulse invariant. To address the study aim, three FLM were considered: FLM_1 including only GRF as a functional covariate; FLM_2 including GRF as a functional covariate and LMV as a scalar covariate; and FLM_3 including GRF as a functional covariate and HJM as a scalar covariate.

To evaluate the FLM, the package fda.usc (function fregres.lm, version 2.0.2) (Febrero-Bande and Oviedo de la Fuente, 2012) was used within the R software environment. In Eq. (1), the continuous functional covariates f_{ij} needed to be approximated using a series expansion with respect to an orthonormal basis system. Cubic B-splines ϕ_k were exploited, a system of basis often used for GRF data (Dannenmaier et al., 2020), with equidistant breakpoints. The number of B-splines n_b serves as a smoothing parameter and determines the variability of parameter estimates and predictions. To mitigate bias in choosing n_b, a range of values from 4 to 18 was considered. Setting $f_{ij} \approx \sum_{k=1}^{nb} c_k^{ij}\phi_k(t)$ and $\gamma(t) \approx \sum_{k=1}^{nb}\widetilde{\gamma}_k\phi_k(t)$ yields the approximate model:

$$Y_{ij} = a + X_i^T\beta + \sum_{k=1}^{nb} c_k^{ij}\widetilde{\gamma}_k + \epsilon_{ij} \tag{2}$$

To evaluate the predictive performance of the considered models, a group cross-validation estimate of the mean squared error of prediction (MSEP) was used, which recognizes the hierarchical structure of the data:

$$\widehat{\mathrm{MSEP}} = \sum_{i=1}^{n}\left[\frac{1}{n_i}\sum_{j=1}^{n_i} Y_{ij} - \frac{1}{n_i}\sum_{j=1}^{n_i}\left(\widehat{a}_{-i} + X_i^T\widehat{\beta}_{-i} + \sum_k c_k^{ij}\widehat{\gamma}_k^{-i}\right)\right]^2 \tag{3}$$

In Eq. (3), $\widehat{a}_{-i}$, $\widehat{\beta}_{-i}$, and $\widehat{\gamma}_k^{-i}$ refer to estimates obtained from the subsample with all data from patient i omitted. This ensures independence between estimates and observed values for patient i.

The quality of the FLM prediction was compared to predictions obtained without use of any covariates, that is, using a reference model (RM) $Y_{ij} = a + \epsilon_{ij}$. The RM may be considered as a mean model that predicts the HCF impulse Y by the mean of the observed HCF impulses from the sample. The RM may be considered as a naive predictor that does not use any GRF, HJM, and LMV measurements, i.e.$\beta = 0$ and $\widetilde{\gamma}_k = 0 \forall k$ in Eq. (2). The results are reported in terms of gain in MSEP as shown in Eq. (4):

$$Gain\ in\ MSEP = 1 - \frac{MSEP_{FLM}}{MSEP_{RM}} \tag{4}$$

Values larger than 0 reflect improved prediction when using the FLM, with a value of 1 indicating perfect prediction. A schematic of the data analysis pipeline can be found in Fig. 2. Finally, as a range of values for the B-splines n_b was considered, multiple $MSEP_{FLM}$ values were obtained, along with multiple values for gain in MSEP. To evaluate the predictive performance of the models, the maximum gain in MSEP is reported here, with all values provided as Supplementary Material.

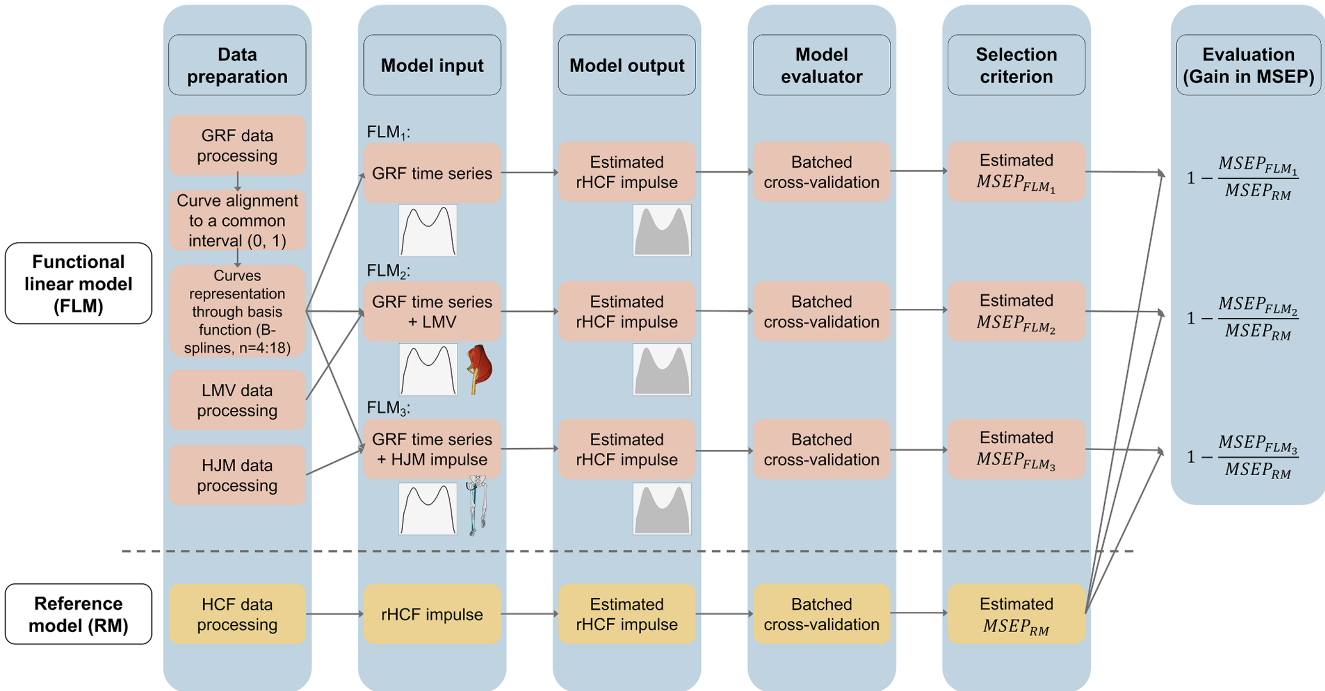

Fig. 2. Schematic of the data preparation, data analysis, and post-evaluation pipeline to predict the *in vivo* resultant hip contact force (rHCF) impulse using functional linear modeling (FLM) with different combinations of functional and scalar covariates as input data. FLM_1 included as functional covariates the ground reaction force (GRF) time series data; FLM_2 included as functional covariates the GRF time series data and as scalar covariates the lean muscle volume (LMV); FLM_3 included as functional covariates the GRF time series data and as a scalar covariate the external hip joint moment (HJM) impulse. To evaluate the quality of predictions, the gain in mean squared error of predictions (MSEP) was obtained.

3. Results

On average, the THA patients were assessed 51.5 ± 10.3 months after surgery. Individual and mean demographic and anthropometric data, LMV values, *in vivo* rHCF and HJMs in the frontal and sagittal plane of the ipsilateral hip impulses are reported in Tables 1, 2 and 3, respectively. The individual time-normalized and mean GRF waveforms for all components collected during gait for the THA limb are displayed in Fig. 1.

Following FDA analysis, the maximum gain in MSEP was obtained to evaluate the FLMs that best predicted the rHCF impulse (Table 4). The complete results for all the number of basis functions used with each FLM are reported in the Supplementary Figs. 1–4). Predictions of the rHCF impulse based on FLM_3 using the GRF time series data as functional covariates and sagittal HJM impulse as scalar covariates yielded the highest maximum gain in MSEP, particularly when coupled with the xGRF (0.92). The frontal HJM impulse did not appear to improve rHCF impulse predictions. Next, the FLM_2 using the GRF time series data as

Table 1
Sex, age, body mass, height, and body mass index (BMI) of patients at approximately 50 months after total hip arthroplasty.

Patient	Sex [female/male]	Age [years]	Body mass [kg]	Height [m]	BMI [kg/m^2]
H2R	M	67.0	86.0	1.72	29.1
H3L	M	65.0	86.0	1.68	30.5
H4L	M	55.6	85.0	1.78	26.8
H5L	F	67.6	80.2	1.68	28.4
H6R	M	72.3	86.3	1.76	27.9
H7R	M	56.8	90.1	1.79	28.1
H9L	M	57.4	127.1	1.81	38.8
H10R	F	55.9	102.5	1.62	39.1
M ± SD	–	61.8 ± 6.2	92.9 ± 14.3	1.73 ± 0.06	31.1 ± 4.6

Note: *M* = mean, *SD* = standard deviation.

Table 2
Lean muscle volume of the gluteus minimus, gluteus medius and gluteus maximus for the ipsilateral limb of each patient with an instrumented hip implant at approximately 50 months after total hip arthroplasty.

Patient	Lean Muscle Volume [cm^3]		
	Gluteus minimus	Gluteus medius	Gluteus maximus
H2R	26.7	86.2	243.9
H3L	18.6	118.4	188.7
H4L	21.1	113.4	244.4
H5L	18.8	93.4	138.9
H6R	26.5	99.6	227.9
H7R	23.9	122.2	284.3
H9L	22.6	104.1	240.3
H10R	27.1	133.0	262.3
M ± SD	22.9 ± 3.3	106.5 ± 16.2	225.5 ± 43.8

Note: *M* = mean, *SD* = standard deviation.

Table 3
Mean impulse of the *in vivo* resultant hip contact force (rHCF) and external hip joint moments (HJM) in the frontal and sagittal planes of motion for the ipsilateral side of each patient with an instrumented hip implant measured during gait at approximately 50 months after total hip arthroplasty.

Patient	rHCF impulse [N × s]	External HJM impulse [Nm × s]	
		Frontal plane	Sagittal plane
H2R	1211	30	17
H3L	1382	43	20
H4L	1175	37	19
H5L	1262	31	19
H6R	1288	41	17
H7R	1311	31	27
H9L	1630	50	47
H10R	1295	51	18
M ± SD	1319 ± 140	39 ± 8	23 ± 10

Note: *M* = mean, *SD* = standard deviation.

Table 4
Maximum gain in mean squared error of predictions (MSEP) obtained to predict the resultant hip contact force impulse for patients with instrumented hip implants at approximately 50 months after total hip arthroplasty. Results are based on combinations of functional and scalar covariates as input data for the functional linear models (FLM). FLM_1 included as functional covariates the ground reaction force (GRF) time series data; FLM_2 included as functional covariates the GRF time series data and as scalar covariates the lean muscle volume (LMV); FLM_3 included as functional covariates the GRF time series data and as a scalar covariate the external hip joint moment (HJM) impulse.

		Maximum gain in MSEP
FLM_1	xGRF time series	0.53
	yGRF time series	<0
	zGRF time series	0.15
	rGRF time series	0.15
FLM_2	xGRF time series + Gmin LMV	0.42
	yGRF time series + Gmin LMV	<0
	zGRF time series + Gmin LMV	0.18
	rGRF time series + Gmin LMV	0.22
	xGRF time series + Gmed LMV	0.74
	yGRF time series + Gmed LMV	0.55
	zGRF time series + Gmed LMV	0.85
	rGRF time series + Gmed LMV	0.84
	xGRF time series + Gmax LMV	0.37
	yGRF time series + Gmax LMV	<0
	zGRF time series + Gmax LMV	<0
	rGRF time series + Gmax LMV	<0
FLM_3	xGRF time series + frontal HJM impulse	0.47
	yGRF time series + frontal HJM impulse	<0
	zGRF time series + frontal HJM impulse	0
	rGRF time series + frontal HJM impulse	0
	xGRF time series + sagittal HJM impulse	0.92
	yGRF time series + sagittal HJM impulse	0.84
	zGRF time series + sagittal HJM impulse	0.78
	rGRF time series + sagittal HJM impulse	0.78

Note: xGRF = mediolateral GRF, yGRF = anteroposterior GRF, zGRF = vertical GRF, rGRF = resultant GRF, Gmin = gluteus minimus, Gmed = gluteus medius, Gmax = gluteus maximus.

functional covariates and Gmed LMV as a scalar covariate also yielded maximum gain in MSEP close to 1, particularly when coupled with the zGRF (0.85) or rGRF (0.84). The Gmax LMV and Gmin LMV did not appear to improve rHCF impulse predictions. From the three groups of FLM, the FLM_1 using only the GRF time series data as functional covariates yielded the lowest maximum gain in MSEP. Fig. 3 shows a scatter plot of measured versus cross-validated predicted *in vivo* rHCF impulse for covariates yielding maximum gain in MSEP for each FLM.

4. Discussion

This study provides evidence that, by itself, the GRF time series measured at the foot does not effectively predict the *in vivo* rHCF impulse acting at the ipsilateral hip joint. Conversely, the combination of GRF time series data with the sagittal HJM impulse enabled a better prediction of the *in vivo* rHCF impulse from external measures only. Although direct measurement of *in vivo* rHCF impulse with telemetric hip implants represent the gold standard methodology to determine internal hip loads, such measurements are challenging and not possible in most THA patients. Appropriate estimators of the *in vivo* rHCF impulse based on external measures such as GRF and HJM can be modeled with a FLM approach that allows to reliably investigate cumulative hip loading, making these biomechanical measures ideal targets when providing individualized recommendations to modern THA patients on their gait behavior to avoid hip joint overloading.

The sagittal HJM impulse appears to enhance predictions of the *in vivo* rHCF impulse when combined with any GRF time series component (FLM_1 vs. FLM_3, Table 4, Fig. 3A & C). The HJM in the sagittal plane largely assists forward propulsion, particularly when shifting from hip extension into flexion, progressing the moving leg into the swing phase (Simonsen et al., 2012). The sagittal plane HJM has been suggested as a relevant indicator of HCF in musculoskeletal-based studies (Foucher et al., 2009; Giarmatzis et al., 2015; Wesseling et al., 2015), potentially with a stronger predictive power than the frontal plane HJM (Foucher et al., 2009), confirmed by our *in vivo* findings. When the sagittal HJM impulse is combined with the xGRF, the best *in vivo* rHCF impulse predictions are obtained. Little attention has been given to xGRF in investigations of hip joint loading during gait in THA populations,

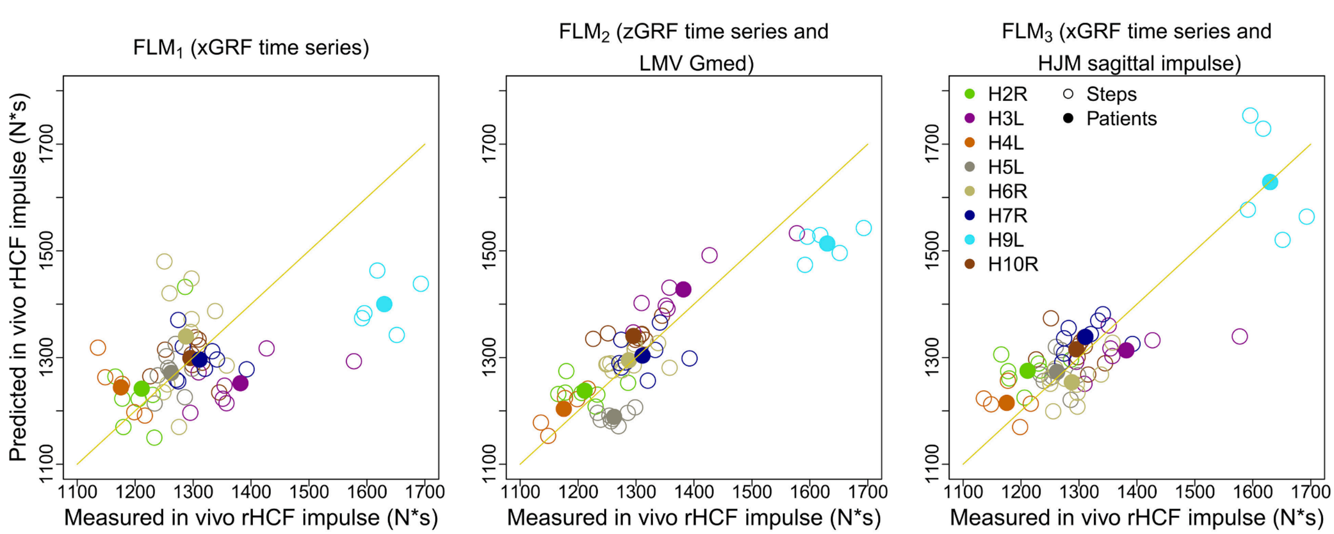

Fig. 3. Scatterplot of measured versus cross-validated predicted *in vivo* resultant hip contact force (rHCF) impulse (N × s) at approximately 50 months after total hip arthroplasty for covariates yielding maximum gain in mean squared error of predictions for each functional linear model (FLM): FLM_1 included as functional covariates the mediolateral ground reaction force (xGRF) time series data (A); FLM_2 included as functional covariates the vertical GRF (zGRF) time series data and as scalar covariates the lean muscle volume (LMV) of gluteus medius (Gmed) (B); FLM_3 included as functional covariates the xGRF time series data and as a scalar covariate the external hip joint moment (HJM) impulse in the sagittal plane (C). For each color group, empty circles represent the impulse for each individual stance phase whereas solid circles represent the mean impulse for each patient. The yellow line represents a 1:1 relationship between measured and predicted *in vivo* rHCF impulse values. A tighter fit of the scatter points represents a smaller error in the predicted *in vivo* rHCF impulse values. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

presumably because xGRF has a much smaller magnitude than the other GRF components (Pandy et al., 2010; Richards et al., 2013). However, our findings suggest that xGRF has a more relevant contribution to hip loading during gait. A potential reason may be related to the regulation of the mediolateral acceleration of the body's center of mass to maintain dynamic balance during forward progression. During most of the stance time, gravity and muscles that lie primarily in the sagittal plane and significantly contribute to body weight support and forward progression (i.e., vasti, soleus, and gastrocnemius), accelerate the center of mass laterally. To actively control and maintain a mediolateral balance, the abductor muscles must act synergistically to oppose the actions of gravity and the referred muscles by accelerating the center of mass medially (Pandy et al., 2010). Consequently, the abductor muscles accelerate the hip into abduction, which generates a counterclockwise hip abduction moment that is transmitted laterally to the ground. For its turn, the ground applies a reaction force, with an equal magnitude and opposite direction: the xGRF (Pandy et al., 2010). Findings from John and colleagues (John et al., 2012) confirmed the abductor muscles as major contributors of the xGRF across multiple walking speeds, supporting the previously referred mechanism required to regulate mediolateral dynamic balance during forward progression (Pandy et al., 2010). Thus, a combination of external measures that reflect forward propulsion (sagittal HJM impulse) and mediolateral balance (xGRF) appears to best predict *in vivo* rHCF impulse, which may be useful for investigating cumulative hip joint loading.

The commonly used zGRF component alone does not appear to be a strong predictor of *in vivo* rHCF impulse. This supports previous findings suggesting that zGRF discrete metrics are unreliable indicators of internal joint loading (Bahl et al., 2020; Giarmatzis et al., 2015; Holder et al., 2020; Loundagin et al., 2018; Matijevich et al., 2019). While the results from the current work do not entirely rule out the zGRF time series as a relevant predictor of *in vivo* rHCF impulse as it yielded a positive gain in MSEP, its combination with the Gmed LMV greatly increases the predictive power from a gain in MSEP of 0.15 to 0.85 (FLM_1 vs FLM_2, Table 4 and Fig. 3B). The Gmed is a key contributor to compressive hip loading (Pandy and Andriacchi, 2010; Valente et al., 2013) and zGRF (Anderson and Pandy, 2003). The mechanical relationship between zGRF and Gmed may reflect the strategy used to recruit zGRF to maintain a mediolateral equilibrium in the frontal plane. This mechanism is relevant to guarantee an adequate dynamic balance by keeping the pelvis stabilized and parallel to the ground throughout the entire stance phase (Correa et al., 2010; Neptune and McGowan, 2016; Solomonow-Avnon et al., 2016). Thus, *in vivo* rHCF impulse is also predicted by a combination of measures that reflect vertical loading (zGRF) and mediolateral stabilization (Gmed).

This study has limitations. The results of the statistical analysis require cautious interpretation because of the small sample size. The estimated MSEP used to compare models is of high variability due to the small number ($n = 8$) of patients, high within-patient variability of the considered characteristics, and the high variability of the estimates in the training samples. Also the barefoot gait condition limits its generalizability to shod conditions. Although barefoot gait allows the direct application of the GRFs to the foot and improved segment motion tracking, barefoot and shod gait can result in different hip joint kinetics (Bergmann et al., 1995; Keenan et al., 2011; Palmowski et al., 2021). Finally, the measurements evaluated in this work were collected at approximately 50 months after THA; thus, it remains unclear whether the results also apply to different follow-up times, which is particularly relevant to monitor joint loading during early THA rehabilitation. Finally, generalizability of the results to other populations without a THA or in a different age range needs further clarification.

Taken together, our results demonstrate that a combination of external measures with a functional linear modeling approach is adequate to investigate *in vivo* rHCF impulse. Using gold standard data from patients with telemetric hip implants revealed that a combination of xGRF time series data and sagittal HJM impulse may represent a sensitive and direct means to investigate cumulative joint loading through the rHCF impulse. Results from this work can be used to improve our understanding of the key factors to consider when designing and prescribing strategies to prevent overloading of reconstructed joints in patients after THA. These findings are also relevant for the wearable technology field, suggesting that the commonly used zGRF variable may not be an adequate surrogate of internal hip loading.

CRediT authorship contribution statement

Sónia A. Alves: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Jörg Polzehl:** Writing – review & editing, Visualization, Software, Methodology, Formal analysis. **Nicholas M. Brisson:** Writing – review & editing, Methodology, Formal analysis. **Alwina Bender:** Writing – review & editing, Software, Data curation. **Alison N. Agres:** Writing – review & editing, Project administration. **Philipp Damm:** Writing – review & editing, Investigation, Funding acquisition. **Georg N. Duda:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jbiomech.2022.111037.

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