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Hip contact forces can be directed outside of a well-oriented cup during common activities; implications for implant testing

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ABSTRACT

Background: Hip replacements are evaluated under a range of standard tests, including simulations of edge loading of the acetabular cup. The study aim was to provide data for the improvement of preclinical testing methods through patient-specific musculoskeletal simulation of daily activities that quantify the direction of hip joint loading relative to the orientation of the cup.

Methods: Musculoskeletal modelling data for five total hip patients were analysed for walking, sit-to-stand, and step down. Simulated implant alignment translational and rotational variations were included (cup implantation orientations: inclination 30–50°, version 12–32°). Dynamic cup orientations were determined based on pelvic rotation. The angles between the load vector and cup pole, force while past the rim, and locations on the cup rim where the vector left and returned into the cup were calculated.

Findings: No forces external to the cup occurred under sit-to-stand or step down. All external forces were directed anteriorly during swing phase, loading with the largest direction changes typically started anteroinferiorly and swept superiorly. The maximum angle between the load vector and cup pole (127°) and maximum external force (245 N) were similar between the worst cases from this dataset and current ISO standard. The largest sweep around the rim was 18°, compared to 0° in the ISO loading, however, and the ISO loading is directed to the superior rim edge.

Interpretation: The current ISO profile may underestimate the potential for liner fixation feature damage or squeaking from the load vector passing around the rim.

1. Introduction

Pre-clinical testing for new total hip replacement (THR) designs includes evaluations under ‘standard’ conditions (ISO 14242-1, 2014) as well as a range of adverse conditions designed to represent different clinically relevant, and more severe, scenarios such as impingement (ASTM F2582–20, 2020) or third-body wear (Cowie and Jennings, 2021). One such scenario is edge loading (ISO 14242-4, 2018), where the femoral head is dynamically translated relative to the acetabular cup using additional loading directed outside the cup rim. This replicates a form of hip joint instability driven by either joint laxity, tissue tension imbalances, or both, without the need for concurrent hip impingement. It induces contact between the head and acetabular liner rim through a relative head-cup translation (termed ‘separation’). The purpose of this standard is to test the resilience of the liner rim region to cyclic loading from the head as well as the wear interaction between the head and liner materials under different contact pressure, sliding, and lubrication conditions than are present at the bearing surface. The standard was developed with reference to stripe wear seen on explanted devices (Nevelos et al., 2000) rather than being directly derived from in vivo motion and force data.

Patient-specific computational modelling studies have simulated the human musculoskeletal system with the addition of a hip replacement and have predicted the possibility of edge loading without impingement for certain cup orientations (Danaei and McPhee, 2022; Kwon et al., 2012; Mellon et al., 2015; Vasiljeva, 2019; Wesseling et al., 2016). Due to the absence of impingement this indicates the possibility for this instability to be driven by the loading and soft tissue constraint environment of these hips. Separation, typically <5 mm, has also been measured in vivo using clinical imaging approaches such as fluoroscopy (Blumenfeld et al., 2011; DeCook et al., 2020; Dennis et al., 2001; Glaser et al., 2008; Komistek et al., 2002; Lombardi Jr. et al., 2000; Sato et al.,

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2017). These investigations included a range of activities such as gait, pivot, shoe tying, sit down, stand up, hip abduction/adduction, and stepping in place. Translations of this magnitude would not be large enough to generate a complete dislocation of the joint, which would be immediately apparent, nor would it be expected to directly generate any obvious discomfort for the patient. Potential long-term consequences, such as increased wear or implant fatigue (Furmanski et al., 2009), however, could cause significant problems if left unchecked and could limit the implantation lifetime of a device. The in vivo measurements of edge loading to date do not include assessment of the hip loads during those events. The separation behaviour induced by the current ISO standard could therefore be improved with more relevant loading characteristics that would better predict the performance of new clinical devices.

Myers et al. (2018) previously used a rigid-body dynamics model to investigate the effect of implant alignment on hip joint loading. The cup position, and stem position and orientation, were varied parametrically and the effect on the hip joint contact force (JCF) was recorded. Altering the cup or stem position, or the stem orientation, affected both the magnitude and direction of the hip JCF.

If the load vector from the Myers et al. dataset was ever directed outside the rim for well-positioned cups this could represent the initial impetus for joint separation. These loading environments would then provide data against which to compare current preclinical testing methods. The objectives of this study were:

1. To identify whether hip JCFs external to the cup bearing surface occur during the modelled activities and if so, during which activities.
2. To compare different cup implantation orientations within the clinical range and establish whether some orientations are more likely to lead to external forces than others.
3. To investigate a clinically relevant range of alignment modifications simulated by Myers et al. (2018), and establish the sensitivity of loading past the rim to those alignment changes.
4. To select example worst-case scenario loading profiles from the dataset and compare them to the current ISO profile, identifying any characteristics that might be important to incorporate into future device validation methodologies.

2. Methods

2.1. In vivo measurement and musculoskeletal modelling

The collection of in vivo data and musculoskeletal modelling that produced the data analysed in this study was described previously by Myers et al. (2018), where the aim was to characterize the effect of implant alignment changes on the muscle and joint contact forces at the hip. Briefly, kinematic and force plate measurements were taken for five THR patients under three activities: walking at a self-selected speed, sit-to-stand, and step down onto the operated leg.

For each participant, a musculoskeletal model was generated using OpenSim version 3.3 (Delp et al., 2007), scaled to the participant height and weight, and calibrated to isometric strength testing results. The calibration of muscle maximum isometric parameters was performed by increasing or decreasing the maximum force for each muscle to minimize differences between model-predicted and measured maximum isometric joint torques on each patient in all three degrees of freedom. A series of hip alignment modifications were performed on the operated leg to represent the estimated clinical variation in implant positioning in each axis, in increments of 1 mm or 1°, up to +/− 3SD (standard deviations) (Tsai et al., 2014) (Table 1). Alignment perturbations were created by altering neutral pose joint centres and stem version (baseline 10° anteversion), relevant attachment sites, and wrapping paths to achieve a given translation or rotation to the implant. When applying the recorded in vivo motions and forces, the musculoskeletal model outputted the resulting magnitude and direction of the joint contact force for each combination of participant, activity, and alignment perturbation. These results were used as the input data for this study, along with the participant-specific pelvic rotations.

2.2. Orientation of load relative to the acetabular cup

For each combination of participant, activity, cup orientation, and joint alignment, the orientation of the resultant load vector relative to the acetabular cup pole was calculated for all time points through the activity.

All input pelvic rotation angles and force vectors were initially converted into a pelvis frame of reference (X: positive right, Y: positive anteriorly, Z: positive superiorly, right hand rule for positive rotations), for compatibility with existing tools (Vasiljeva, 2019, 2022). Implant alignment changes used the same positive/negative directionality. From an initial cup implantation orientation, the pelvic rotation angles from each activity were applied to calculate the dynamic cup orientation. Pelvic rotations were applied as Euler angles in the order YZX.

To identify cases where the load vector was directed outside the cup, a cup coverage angle of 180° was assumed, meaning that an angle from the pole of greater than 90° would indicate an externally directed force. All calculations were performed using Python 3.11.

2.3. Study design

The analysis included three activities, five participants, and eight translation/rotation implant alignment perturbation directions. In the source study, the perturbations in implant alignment were only applied to the operated hip (termed “op”). In the source study, the cup rotational orientation had no effect on the centre point, range of motion, or action of the joint and therefore was not varied. For this study, a baseline cup implantation orientation of 40° radiographic inclination and 22° radiographic version (shorthand RI/RV = 40°/22°) was used with a clinically acceptable ±10° range of variability. This was selected by using the mean and accepted variation measured from a published study of 400 cups (Antoniades et al., 2023).

The vector analysis with the native, or unmodified, joint alignment was performed for both the operated and non-operated/natural hips. The effect of the hip joint alignment perturbations was investigated on the operated hip only. Data was analysed for alignment perturbations at both 1 and 2 standard deviations (SD) from the native case (Table 1). This ensured that trends and extremes were captured and understood across a wider range (±2SD), but that data and final profiles were presented for more clinically likely combinations with less susceptible to modelling uncertainty (±1SD). Cases were compared using the maximum angle between the load vector and cup pole, maximum force while past the rim, and maximum sweep angle (angle change of the load vector, in the cup face plane, while outside the cup). These measures were also calculated for the ISO standard protocol for comparison,

Table 1
Magnitudes and directions by which the implant alignments were perturbed, using an approximation of 1 or 2 SD (standard deviation) of typical clinical variance. ML = mediolateral, AP = anteroposterior, SI = superoinferior, ANT = anteversion/retroversion, ABD = abduction/adduction.

Implant	Translation/Rotation direction	±1SD clinical variance	±2SD clinical variance
Cup	ML Translation	2.7 mm	5.4 mm
Cup	AP Translation	2.7 mm	5.4 mm
Cup	SI Translation	2.6 mm	5.2 mm
Stem	ML Translation	4.9 mm	9.8 mm
Stem	AP Translation	6.3 mm	12.6 mm
Stem	SI Translation	5.1 mm	10.2 mm
Stem	ANT Rotation	11.9°	23.8°
Stem	ABD Rotation	7.2°	14.4°

assuming that no separation occurred to match the action of the model.

Four steps were used to narrow down from broad patterns to specific cases of interest:

1. Initial test of the full dataset to identify which participants and activities resulted in loading past the cup rim (> 90° maximum angle between load vector and cup pole), and where, relative to the rim, this was directed.
2. Sensitivity test varying cup implantation orientation. This was used to identify worst-case cup implantation orientations.
3. Sensitivity test perturbations to the operated hip joint alignment. This was used to identify worst case perturbation directions for the joint alignment and therefore select candidate profiles for further evaluation in edge loading testing models.
4. Comparison to the existing ISO standard protocol to identify any potentially important differences that should be tested to evaluate whether they generate a more severe, more clinically representative, test protocol.

3. Results

The data associated with this paper is openly available from the University of Leeds Data Repository (Etchels et al., 2025).

3.1. Hip load vector direction across three activities

Within each activity the load path displayed similar trends across the five participants, and the profiles were previously reported as having good agreement with the patients from Bergmann et al. (2010). Out of the three activities, only the walking activity produced loading past the rim in the baseline case: a 40°/22° cup and no modification to the native joint alignment. Both the operated and non-operated hips were analysed and, for one participant, the occurrences of loading outside the rim were for both hips (Fig. 1 A).

Walking predominantly directed the load vector to the superior side of the cup, with the load extending anteriorly during swing phase. In the sit-to-stand activity, the loading path entered the superior side and inferoposterior region of the bearing surface (Fig. 1 B). In step down, the load vector was focused in the superoanterior region (Fig. 1C).

3.2. Direction and extent of loading past the rim

Loading past the rim occurred in three out of five participants when the analysis was performed across a wider set of scenarios, with the initial cup implantation orientation varied by ± 10° in both inclination and version, and the joint alignment by ± 2SD of clinical variability (Fig. 2). All occurrences of loading past the rim were for the walking activity, and all occurred during swing phase on the anterior side of the cup.

Any instances of loading past the rim with a duration of only one data were visualised for position on the cup rim (Fig. 2) but excluded from further analysis. Two occurrences of loading past the rim persisted for only a single data point (frequency 100 Hz). These were the result for participant p2 and the 2nd occurrence of loading past the rim for p4, which was also the loading past the rim which occurred with a native joint alignment.

3.3. Worst case scenario by cup orientation

The effect of cup orientation was investigated across all remaining cases where the load passed the rim. The effect of increasing and decreasing inclination and version angle on the three key output measures was generally consistent between different initial cup orientations and a representative example for p4 and p5 (with 1SD of stem abduction) is given in Fig. 3.

Increasing cup version angle resulted in increases to the maximum angle between the load vector and cup pole, maximum force while past the rim, and maximum sweep distance of the load vector around the cup rim (Fig. 3). Decreasing inclination angle also increased these three values for almost all patients and alignment directions. With a 2SD superior stem translation, however, the maximum sweep angle increased from 13° at 30° inclination to 15° at 50°.

3.4. Worst case scenario by joint alignment

The effect of different directions of joint alignment alteration at the stem and cup was then investigated. For the 30°/32° cup orientation, which generated the most severe cases of loading past the rim, the effect of ±1SD of alignment change is given in Fig. 4.

ML translations to the cup had opposite effects on p4 and p5 (Fig. 4A), but all other alignment directions had the same effect (either increase, decrease, or no effect) on the maximum angle between the cup pole and load vector, the force while past the rim, and the sweep around the rim for both participants.

Stem abduction (the -ve direction) and stem superior translation (the +ve direction) had the largest consistent effect over both participants. Stem abduction gave the largest angle load to pole, force past rim, and sweep for p5. For p4 it also gave high values for all three outputs. For p4 only, the highest angles from the cup pole and sweep around the rim came from posterior or superior stem translations. The highest force past the rim was from the posterior stem translation.

Two worst-case scenarios were selected from the current data set for comparison to the current ISO standard. Case 1 used participant p4's gait cycle data with a 30°/32° cup implantation orientation and a

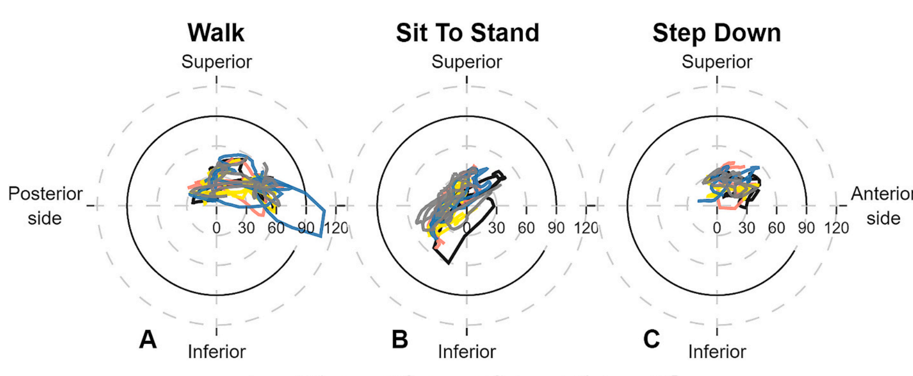

Fig. 1. Hip contact force direction, as an angle between the force vector and the pole of the cup and a direction relative to the superior-most point on the rim with a neutrally aligned pelvis, for the three activities(A: Walk, B: Sit to stand, C: Step down), for all participants (p1 – p5) and both hips. All results for the native joint alignment and for a cup implanted at RI/RV 40°/22°.

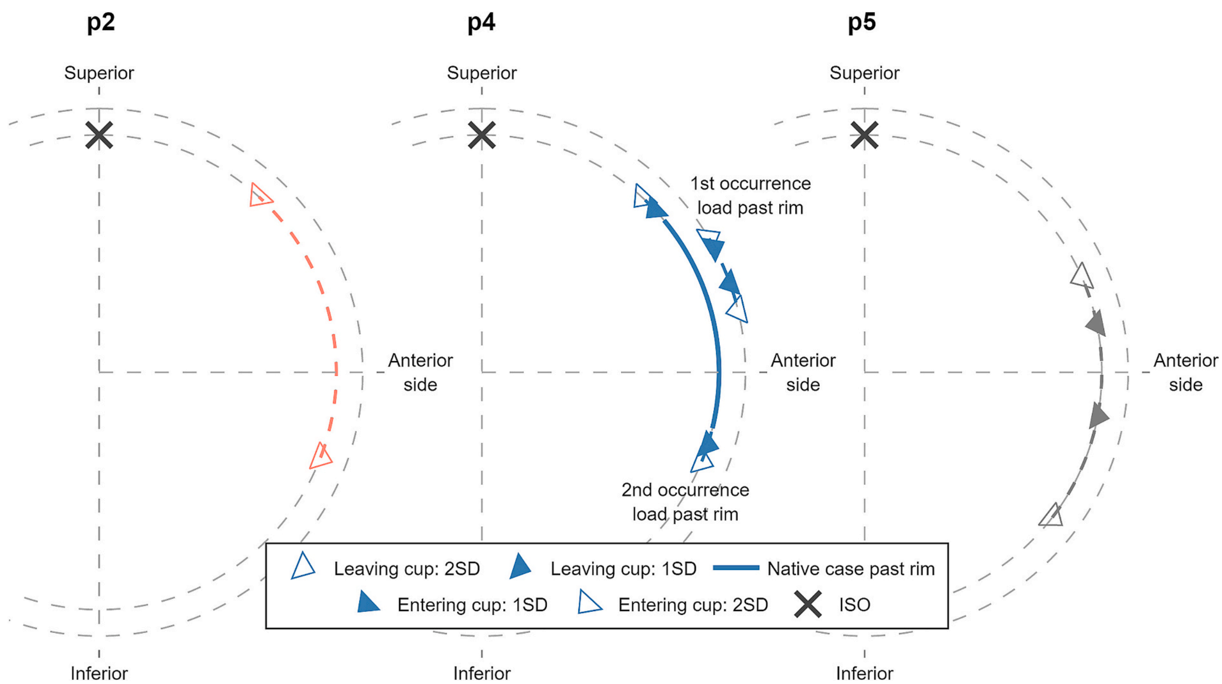

Fig. 2. Range of directions of the load vector when it was past the rim, relative to the cup face and superior-most point on the rim with a neutrally aligned pelvis. Data is presented for the three participant models which generated loading past the rim (p2, p4, p5), all during walking. Each marker indicates the extremes across all cup implantation orientations, and across joint alignment perturbations representing 1 or 2 standard deviations (SD) of clinical variability. The solid line represents the extremes across all cup orientations with a native joint alignment only. For p4 the load vector left the rim on two separate occasions during some cases, and these are given by two separate traces.

posteriorly translated stem. This case maximised the hip JCF while the load vector was directed outside the cup, though several other alignment directions also led to a very similar peak hip JCF. Case 2 used participant p5*'s* gait cycle data with a *30°/32°* cup implantation orientation and an abducted stem and maximised the past it. Cases 1, 2, and the current ISO profile are summarised in Table 2.

The current ISO standard generates loads at an angle from the pole, and magnitude during swing, that are similar to those seen in the current data with ~2SD of joint alignment variation. Case 2, however, includes a direction change to the load vector where it sweeps around the face of the cup by 8–18°. This is not mimicked within the current ISO test profile.

3.5. *Time-series detail of selected worst-case scenarios*

Results through the activity cycle for the dynamic cup orientation (Fig. 5A), hip contact force (Fig. 5B), and angle between the load vector and cup pole (Fig. 5C) are shown in Fig. 5 to describe the loading environments created by the two cases. Additional data is included in the associated data packet (Etchels et al., 2025). For these participants the operated hip was the right hip.

4. Discussion

This study investigated the frequency and severity of loading outside the bearing surface of cups implanted at various radiographic inclinations and versions, across a dataset of five participants and three activities and with variations to implant alignment. After removing occurrences of load past the rim for only one time point, it was found that loading past the rim occurred for walking, for two out of five participants. This occurred towards the superoanterior side of the cup, and the load vector swept along the rim while past it. This superoanterior directionality of loading past the cup rim is supported by evidence from Wesseling et al. (2016) in an analysis of 405 gait patterns using a similar musculoskeletal modelling derived hip force approach.

Two worst-case scenarios identified, based on equivalent or elevated risk of edge loading severity when compared to the existing ISO standard. These cases reached a maximum force while past the rim (case 1) and a maximum angle between the load vector and cup pole (case 2) which were similar to the ISO standard. However, the directionality of the load vector and potential for sweeping around the rim, were significantly different to the existing ISO profile. In the ISO standard the load vector direction is always in the frontal plane with no version angle applied to the cup. It therefore directs towards the superior-most point on the cup rim, when viewed in the cup face plane. The angle between the load vector and cup pole then varies with time according to the applied vertical load. Conversely, the loading past the rim seen in the participant models used in this study was directed anteriorly and swept around the rim while past it. This change in direction may be of importance for predicting device performance. The addition of a friction force acting circumferentially around the liner rim could be consequential for liner fixation, particularly if liner thicknesses reduce to minimize dislocation risk (Cooper et al., 2024).

The occurrence in vivo of head to cup rim contact, independent of impingement, is supported by fluoroscopy imaging (Blumenfeld et al., 2011; DeCook et al., 2020; Dennis et al., 2001; Glaser et al., 2008; Komistek et al., 2002; Lombardi Jr. et al., 2000; Sato et al., 2017) and retrieval evidence. Wear indicative of edge loading, such as stripe wear scars, have also been observed in retrievals (Abdel et al., 2014; Affatato et al., 2011; Esposito et al., 2012; Furmanski et al., 2009; Govind et al., 2015; Nevelos et al., 2000; Restrepo et al., 2008; Walter et al., 2004, 2011; Yamamoto et al., 2005). For hard-on-hard bearings, contact that sweeps around the rim of the liner might also increase the risk of in vivo squeaking, which has been linked through retrievals to high rates of edge wear (Walter et al., 2011).

These results should be interpreted in a specific and limited way. In this study, the hip joint was constrained to a single point. The results therefore represent a force environment that could induce relative translation at the joint, but the model did not include a representation of the joint capsule and could not create that relative motion and predict

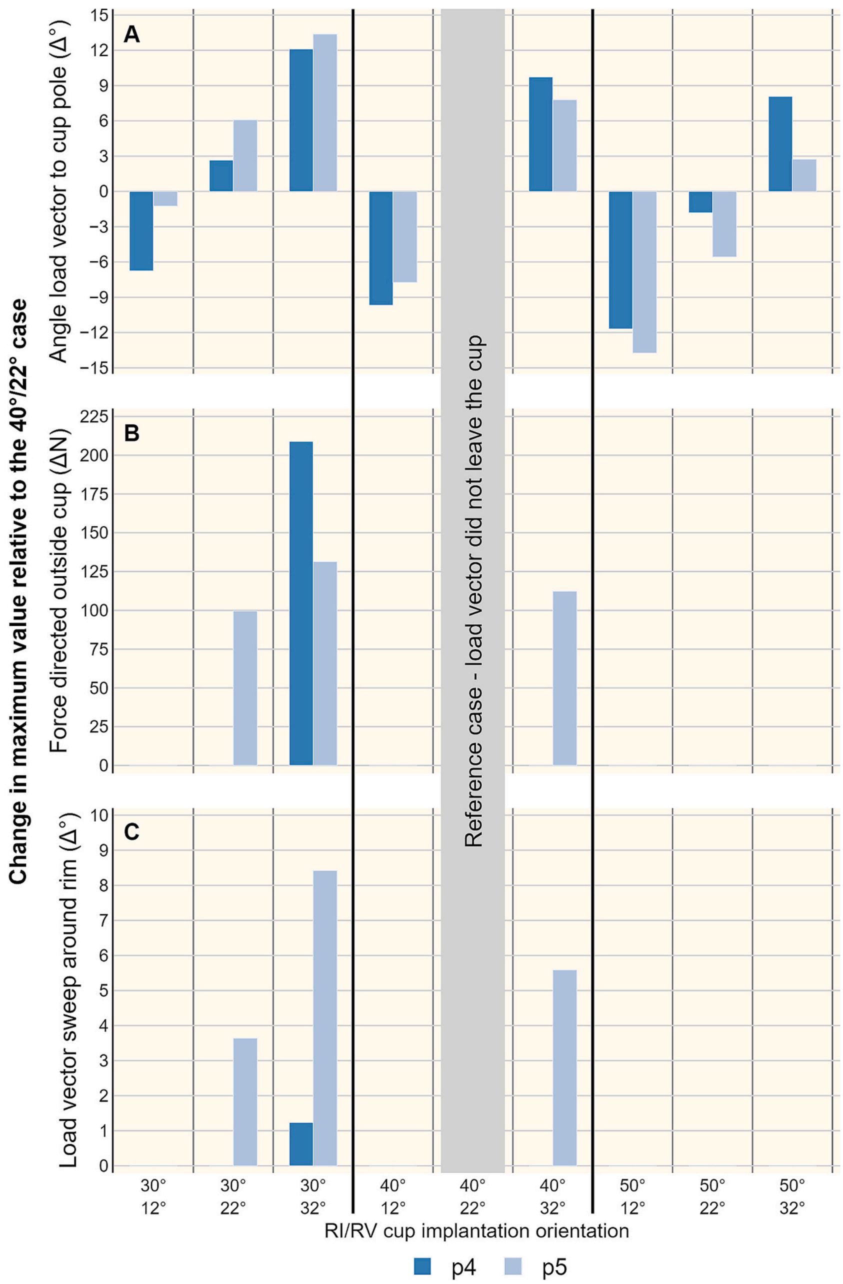

Fig. 3. Change to the (A) maximum angle between the load vector and cup pole, (B) maximum force while past the rim, and (C) maximum swept angle around the rim, from the 40°/22° cup implantation orientation result for all other cup orientations. Case: participants p4 and p5, 1SD of stem abduction, operated limb, walking. The load vector for the reference case did not pass outside the rim, as such the changes in B and C also represent the total force and sweep.

the actual resulting joint force. Similarly, the loading outside the rim predicted in these models should not be thought of as an indicator of dislocation. The loading would induce a translation, but dislocation risk would require insufficient soft tissue constraint to counteract these forces, and the forces acting at the moments are relatively small (<250 N). The data from this study gives us an indication of force direction, sweep and timing of potential separations. The clinical significance of these externally directed loads is yet to be determined.

The next step requires combining this with models of the hip that include the capsular restraint, allowing for relative translations across the hip joint, which would provide predictions of the separation that these cases might cause and would enable a closer comparison to the published literature than is possible here. Force data from instrumented hip implant studies, such as Bergmann et al. (1993), is regularly used as a comparison point or modelling input for computational research. However, the direction of the load measured by those devices includes the influence of any edge loading that may be present within the joint, making it impossible to separate all the necessary factors.

Although the specific metrics are different, there are similarities between the broad findings in this work and those of LaCour et al. (2020), whose model included the hip capsule and predicted that separations sufficient to induce edge loading were possible during gait. In this study, the cup orientations which corresponded with higher edge loading risk were higher version angles and lower inclination angles. This was because the loading past the rim occurred superoanteriorly and increased version reduced the cup coverage in this direction. Low inclination angles generally increased how far the load vector moved past the rim, the peak force while past the rim, and how far around the cup face the load vector direction changed while past the rim. LaCour et al., found an increase in maximum separation within increased

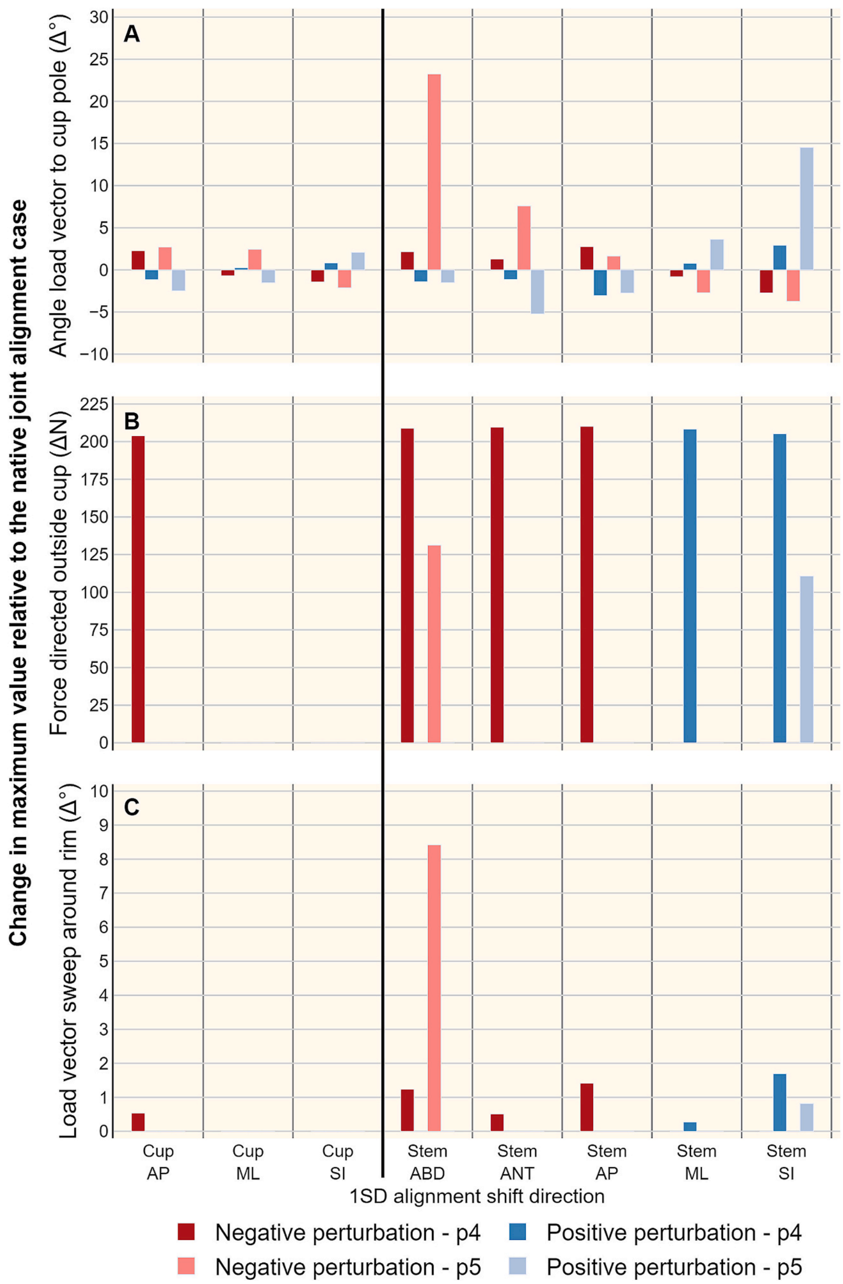

Fig. 4. Change to the (A) maximum angle between the load vector and cup pole, (B) maximum force while past the rim, and (C) maximum swept angle around the rim, from the native joint alignment result when each implant alignment direction was altered by ±1SD. Case: participants p4 and p5, RIRV 30°/32°, operated limb, walking. The load vector for the reference case did not pass outside the rim, as such the changes in B and C also represent the total force and sweep.

Table 2
Summary of the final two selected worst-case scenarios recommended for further evaluation and the existing ISO protocol. Case 1 and Case 2 results are given as a range covering 1SD and 2SD of alignment variation. The ISO maximum resultant force was calculated using a 100 N/mm spring with effective stiffness of 55 N, taking into account fixturing compliance, and 4 mm compression, and a 70 N axial vertical load.

Cup implantation orientation (RI/RV, °)	Max angle load vector to cup pole (°)	Max resultant force while past rim (N)	Max sweep angle around rim (°)
Case 1: p4, gait, 30°/32°, −ve Stem AP.	92–95°	210–245 N	1–2°
Case 2: p5, gait, 30°/32°, −ve Stem ABD.	100–127°	131–169 N	8–18°
Current ISO 14242:4	~127°	~230 N	~0°

version (from 15° to 35°). (It is interesting to note that their predicted separations were generally minimal when positioning the cup to match the anatomy of the natural acetabulum.) Both studies found that varying the simulated post-operative joint alignment altered the measures used to indicate edge loading.

The variation in occurrence of externally directed loads across the five participants indicates that patient factors also have substantial influence on edge loading risk. However, analysis of those patient factors is out of scope of this study. The low number of participants in the current study mean that the findings may not generalise to wider populations, where prevalence of externally directly loads is not clear, and more severe cases could potentially be found. There is limited representation of diversity within the participant group, and a small sample cannot capture differences in the wider patient population that are driven by various protected characteristics (Hill et al., 2020). However,

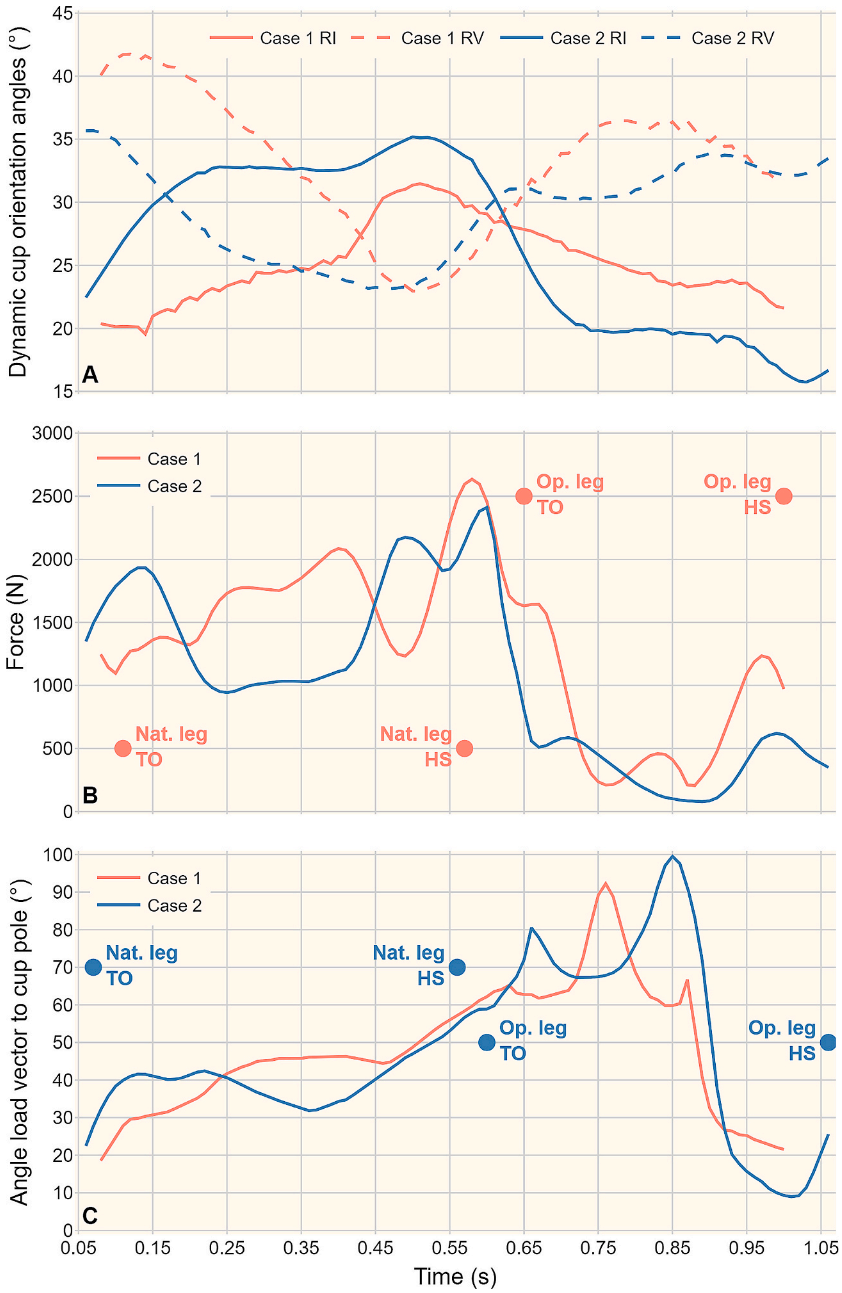

Fig. 5. Results through the walking cycle for the two cases selected by screening the entire dataset, with 1SD of joint alignment alteration. Case 1: highest force while past the rim, Case 2: highest angle of load past rim and sweep of load around the cup face while past the rim. (A) Dynamic cup radiographic inclination (RI) and version (RV) angles. (B) Resultant hip force through the cycle. (C) Angle between the load vector and the cup pole. The beginning and end of swing for both the operated and natural leg are labelled for context: Op. leg = operated leg, Nat. leg = natural leg, TO = toe-off, HS = heel-strike.

these results do demonstrate a potentially important feature of edge loading which is not currently captured in standardised testing. If future experimental work demonstrates that sweep around the rim is important to device performance, then further work will be required to discover the prevalence and severity in a wider, more diverse population.

A limitation affecting all computational analysis of edge loading is the challenge of predicting hip joint forces during swing phase. The joint loading during this phase is small and therefore more sensitive to some forms of measurement error, and there are no measured external forces on that leg to use as inputs to, or validation of, the optimisation. There is currently no ideal way to overcome this limitation. However, it is encouraging that both the current work and that of LaCour et al. (2020) suggest the potential for separation/edge loading to occur under normal gait conditions, and without forced levering of the head onto the rim via impingement. This reinforces the importance of understanding and accounting for these conditions in device testing.

5. Conclusions

Hip joint load vectors directed outside of the cup were predicted during walking in patients with a well-positioned implant. This was not seen within this data set for either the sit-to-stand or step down exercise. All loading past the rim was directed anteriorly. The largest sweeping motions of the load vector around the cup rim while past it started more inferiorly, sweeping towards the superior side of the rim before re-entering the main bearing surface. This sweep behaviour is not currently captured in the ISO testing standard for hip replacement edge loading. Loading profiles have been identified that can be used to experimentally investigate whether this change in load direction can impact the results of design evaluations and whether it should be incorporated into future testing approaches.

CRediT authorship contribution statement

Lee Etchels: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Casey Myers:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Funding acquisition, Data curation. **Chadd Clary:** Writing – review & editing, Methodology, Investigation, Funding acquisition. **Paul Rullkoetter:** Writing – review & editing, Resources, Funding acquisition. **Ruth Wilcox:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Alison Jones:** Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Ruth Wilcox reports financial support was provided by UK Research and Innovation. Alison Jones reports financial support was provided by UK Research and Innovation. Ruth Wilcox reports a relationship with DePuy Synthes that includes: funding grants. Casey Myers reports a relationship with DePuy Synthes that includes: funding grants. Chadd Clary reports a relationship with DePuy Synthes that includes: funding grants. Paul Rullkoetter reports a relationship with DePuy Synthes that includes: funding grants. Alison Jones reports a relationship with DePuy Synthes that includes: funding grants. The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Authors are in receipt of research funding from the UK Engineering and Physical Sciences Research Council (EPSRC) (AJ, RW), DePuy Synthes (AJ, CM, CC, PR, RW). AJ and RW are supported in part by the National Institute for Health and Care Research (NIHR) Leeds Biomedical Research Centre (BRC) (NIHR203331). If there are other authors, they 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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Data availability

Data is included in a repository and referenced in the paper (Etchels et al., 2025).

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