

Review

Return to Play After Total Hip Arthroplasty: What Do Instrumented Hip Implants Teach Us? A Scoping Review

Vasileios Giannatos ^{1,*}, Sofia A. Xergia ², Irini Tatani ¹, Panagiotis Antzoulas ¹, Charis Tsarbou ², Nikolaos I. Liveris ², Michalis Kroustakakis ¹, Riccardo Giorgino ^{3,4}, Konstantinos Kafchitsas ¹ and Andreas Panagopoulos ¹

- ¹ Orthopedics Department, University Hospital of Patras, 26504 Patras, Greece; irinitatani@gmail.com (I.T.); p.antzoulas@hotmail.com (P.A.); mikekroustakakis@gmail.com (M.K.); kafchitsas@googlemail.com (K.K.); andpan21@gmail.com (A.P.)
- ² Department of Physiotherapy, School of Health and Rehabilitation, University of Patras, 26504 Patras, Greece; sxergia@upatras.gr (S.A.X.); ctsarpou@upatras.gr (C.T.); n.liveris@upatras.gr (N.I.L.)
- ³ IRCCS Ospedale Galeazzi Sant'Ambrogio, 20157 Milan, Italy; riccardogiorgino93@gmail.com
- ⁴ Department of Precision and Regenerative Medicine and Ionian Area (DiMePreJ), University of Bari Aldo Moro, 70124 Bari, Italy
- * Correspondence: vasileiosgiannatos@outlook.com; Tel.: +30-6945608508

Abstract

Background: Return to play (RTP) after total hip arthroplasty (THA) is increasingly expected by younger and more physically active patients. Current activity recommendations remain heterogeneous and are largely derived from expert opinion and indirect biomechanical modelling approaches, rather than direct in vivo biomechanical evidence. The aim of this article is to systematically map and synthesize the evidence from instrumented hip implant studies and to clarify how direct in vivo telemetry data can inform RTP counselling after THA. **Methods:** A scoping review was conducted according to a predefined Open Science Framework protocol and reported following PRISMA-ScR guidelines. MEDLINE (PubMed) and Scopus were searched from inception. Peer-reviewed clinical studies reporting direct in vivo biomechanical measurements obtained from instrumented hip implants were included. Conference proceedings, technical notes, reviews, and in vitro or computational-only studies were excluded. Data were extracted and synthesized descriptively according to activity domain, biomechanical variables, and implant technology. **Results:** Fifty studies met the inclusion criteria. Early investigations established feasibility and evolved from wired strain-gauge systems to fully implantable telemetric prostheses capable of measuring three-dimensional forces, moments, and friction-related parameters. Across cohorts, level walking consistently produced peak hip contact forces of approximately 2–3 times body weight, serving as a clinically meaningful reference loading envelope. Several recreational activities—including cycling, aquatic exercise, Nordic walking, and most gym-machine exercises—generally remained within or close to this range when performed with controlled technique. In contrast, certain rehabilitation tasks, forward-bent postures, lifting maneuvers, and perturbation events generated loads equal to or exceeding those observed during walking. Importantly, frictional moments and load direction showed substantial variability and may be more relevant to implant fixation than peak force magnitude alone. **Conclusions:** Instrumented hip implants provide objective biomechanical benchmarks that support principle-based and individualized RTP counselling, grounded in directly measured mechanical exposure rather than sport classification alone.

Keywords: instrumented; THA; RTP; biomechanics; telemetry; direct



Academic Editor: George Mihai Avram

Received: 13 April 2026

Revised: 5 June 2026

Accepted: 7 June 2026

Published: 16 June 2026

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1. Introduction

Total hip arthroplasty (THA) has evolved from a procedure primarily aimed at pain relief and restoration of basic mobility into an intervention increasingly expected to support return to sport (RTS) and higher levels of physical activity. As younger and more active patients undergo THA, surgeons are frequently asked to provide guidance regarding safe return to play (RTP). However, current clinical recommendations remain largely based on expert consensus and theoretical biomechanical considerations, rather than direct measurements of the loads experienced by implants during activity [1]. Instrumented hip implants offer a unique opportunity to address this gap by providing direct in vivo measurements of joint loading under real-life conditions, thereby allowing a more objective understanding of the biomechanical environment of the replaced joint (Figure 1) [2].

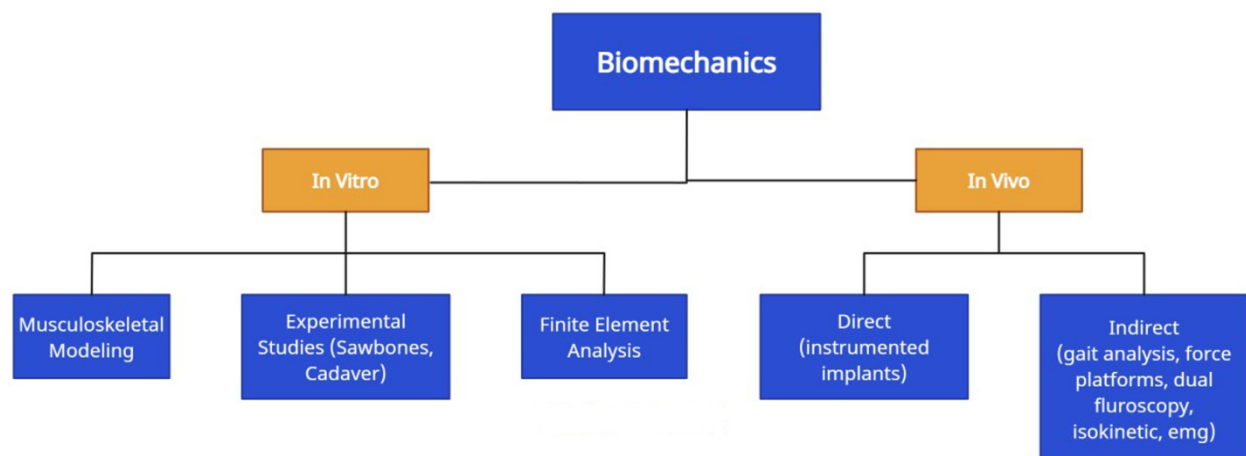


Figure 1. Diagram illustrating the most commonly used methods of biomechanical evaluation. Among these approaches, instrumented implants represent the only technique capable of directly measuring biomechanical parameters in vivo.

1.1. Historic Perspective: Origins of Instrumented Hip Implants

The evolution of THA has been closely intertwined with advances in hip biomechanics. Early understanding of load transfer began with the formulation of Wolff's law in the late nineteenth century, describing bone adaptation to mechanical stress, and was further developed through mechanical models of hip loading during gait in the twentieth century [3]. Early biomechanical investigations relied on simplified two-dimensional static models—such as those describing abductor lever arms and joint reaction forces during single-leg stance—to estimate loading conditions around the hip and to guide prosthetic implant design [4]. With advances in computational power, indirect methods such as three-dimensional motion analysis and musculoskeletal modelling were introduced, enabling the estimation of joint moments and forces during dynamic activities. Nevertheless, these approaches remain dependent on assumptions regarding muscle activation patterns, coordination strategies, and model boundary conditions, which limit their ability to accurately capture the true mechanical environment of the joint in vivo [5]. Recognition of these limitations led to the development of direct measurement techniques, culminating in instrumented hip prostheses capable of recording three-dimensional joint forces, moments, and additional biomechanical parameters in vivo. These technologies provide objective insights into the mechanical environment of the replaced hip joint during functional tasks and have become a critical tool for validating biomechanical models and informing clinical decision-making.

Direct measurement of hip joint forces began in the 1960s and 1970s with strain-gauge equipped prostheses [6,7]. Technological refinement during the 1980s enabled

multi-channel telemetry systems and wireless data transmission [8,9]. The Berlin group led by Bergmann and colleagues subsequently developed fully implantable, hermetically sealed telemeterized prostheses, capable of measuring three-dimensional joint forces and temperature without percutaneous connections [10–13]. These innovations enabled the creation of comprehensive in vivo datasets describing hip joint loading across a wide range of functional activities [11].

1.2. Beyond Forces: Stability and Monitoring Technologies

While joint contact force remains the primary parameter of interest for RTP decisions, complementary measurement approaches contribute to understanding the mechanical environment of THA and long-term implant survivorship. Frictional moments, torsional loads, temperature changes, and implant micromotion have been quantified, highlighting that mechanical exposure after THA is multidimensional and can not be adequately described by peak force alone [13–15]. In addition, statistical methods for averaging the highly variable biomechanical signals have also further improved interpretability of in vivo data [16].

1.3. Clinical Relevance for Return to Play

Return to play after total hip arthroplasty remains a subject of ongoing debate, reflecting the tension between increasing patient expectations for high levels of physical activity and concerns regarding implant longevity and mechanical failure. Surveys of orthopedic surgeons consistently demonstrate variability in RTP recommendations, with most clinicians permitting low-impact activities while discouraging participation in higher-impact sports because of theoretical risks of increased wear, loosening, or dislocation, despite limited availability of direct biomechanical evidence supporting these restrictions [17–19]. At the same time, registry data and clinical series suggest that many patients successfully resume recreational sports following THA, suggesting a potential discrepancy between conservative clinical recommendations and actual patient behaviour [20,21]. Historically, the absence of objective loading data during sport has limited the development of evidence-based RTP guidance, as indirect approaches such as gait analysis and musculoskeletal modelling cannot fully capture the complex forces acting on the hip during dynamic movements. Instrumented hip implant studies, which directly measure joint forces and moments in vivo, offer a potential means to reconcile these uncertainties by quantifying the mechanical demands associated with different activities and informing more individualized recommendations [11]. Furthermore, the potential future commercialization of instrumented prostheses—similar to the recent introduction of the Persona IQ instrumented total knee arthroplasty (TKA) by Zimmer Biomet—may make these technologies increasingly relevant, potentially enabling continuous implant monitoring during daily and athletic activities [22].

1.4. Purpose of This Scoping Review

Despite decades of telemetry research, its implications for RTP after THA remain fragmented across biomechanical, clinical, and engineering literature and have not been systematically synthesized from return-to-sport perspective, with current RTP guidelines relying on indirect modelling an expert consensus, rather than direct biomechanical evidence. The purpose of this scoping review is to map the body of evidence derived from instrumented hip implant studies, summarize current understanding of activity-specific in vivo loading after THA, and examine how these findings inform evidence-based return-to-play counselling and rehabilitation strategies.

2. Materials and Methods

2.1. Study Design

This scoping review was conducted in accordance with a predefined protocol registered on the Open Science Framework (OSF) and was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines (Appendix A) [23].

2.2. Eligibility Criteria

Eligibility criteria were defined according to the Population–Concept–Context (PCC) framework, which is commonly used in scoping review methodology. The population comprised adults aged ≥ 18 years who had undergone total hip arthroplasty. The concept of interest was direct in vivo biomechanical measurements obtained from instrumented hip implants, including parameters such as joint contact forces, resultant force vectors, joint moments or torques, and temporal loading characteristics. Studies relying solely on indirect biomechanical estimation methods, including motion analysis without original biomechanical data.

Studies relying solely on indirect biomechanical estimation methods, including gait analysis without instrumented implants, musculoskeletal modelling, or other simulation approaches, were excluded. Cadaveric, in vitro, computational, and animal studies were also excluded, as they do not provide direct in vivo measurements. Due to the historical development of telemeterized hip implants and the predominance of studies originating from the Charité research group, publications written in English or German were considered eligible.

2.3. Search Strategy and Study Selection

A comprehensive literature search was conducted in MEDLINE (via PubMed) and Scopus from database inception to 6 January 2026. The full search strategies for both databases are included in Appendix B. In addition, the reference lists of included articles and relevant reviews were manually screened to identify additional eligible publications.

2.4. Data Synthesis

Findings were synthesized descriptively using descriptive analytical methods, consistent with recommended scoping review methodology and charted (Appendix C). Findings were summarized through structured and narrative synthesis. Results were organized according to biomechanical measurement type, activity or functional task, and instrumented implant technology. Consistent with the methodological framework of scoping reviews, a formal risk-of-bias assessment was not performed, as the primary objective of this review was to map the existing body of evidence rather than evaluate the methodological quality of individual studies.

3. Results

The initial search yielded 3660 records, including 1853 from PubMed and 1807 from Scopus. All records were imported into Rayyan for screening, where 1007 duplicates were automatically identified and removed. An additional 113 duplicates were removed manually, resulting in 2540 unique records for screening. Two reviewers (VG and IT) independently screened titles and abstracts for eligibility. Exclusion criteria were described above and included technical reports, indirect biomechanics, isokinetic/emg/accelerometer studies, and knee–shoulder–spine studies. This process excluded 2478 studies and resulted in 60 articles for full-text review. Following full-text assessment, 46 studies met the predefined inclusion criteria and were included in the final synthesis. After reviewing the reference list of each included paper, four additional papers eligible for inclusion were identified, reaching 50 papers for

final analysis. Any disagreements between reviewers were resolved through discussion and consensus, with consultation of a third reviewer (SX) when necessary. The study selection process is presented in a PRISMA-ScR flow diagram (Figure 2).

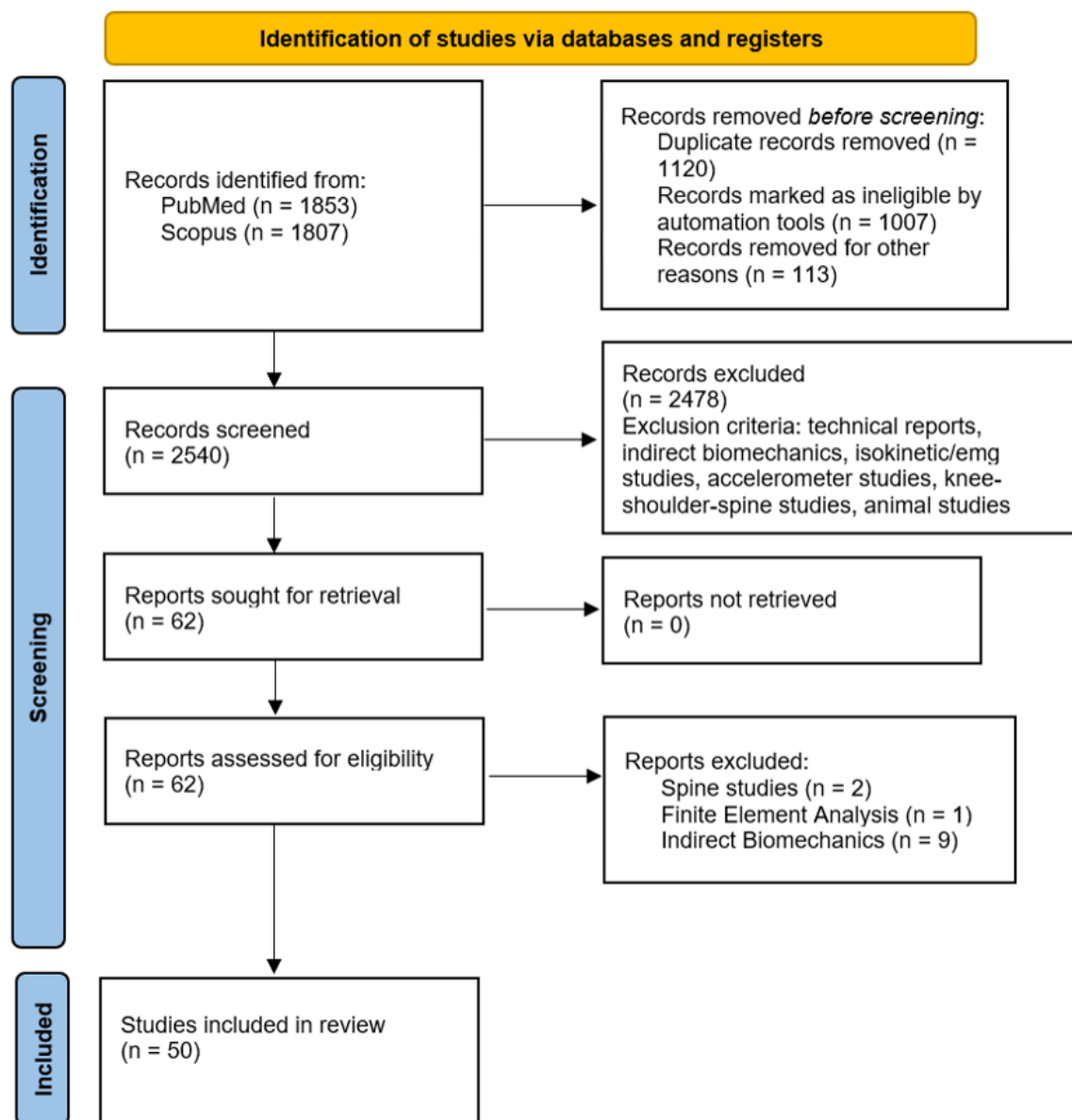


Figure 2. PRISMA-ScR flow diagram illustrating the study identification, screening, eligibility assessment, and inclusion process.

Early instrumented hip implant studies (pre-2000): feasibility and foundational observations.

Early investigations into in vivo hip biomechanics were characterized by rapid methodological evolution as researchers sought practical ways to measure loads within the joint. The earliest studies relied on wired or externally connected strain-gauge prostheses and pressure-instrumented hemiarthroplasties, which demonstrated proof of concept but were constrained by short recording duration, restricted patient mobility, and considerable technical complexity [6,24,25]. Subsequent case reports refined sensor placement and improved pressure mapping, enabling longer observation periods and more detailed characterization of loading patterns during activities such as gait, transfers, and rehabilitation exercises [26,27].

By the late 1980s and 1990s, technological advances—particularly from the Berlin group—shifted the field toward fully implantable telemetry systems capable of wireless data transmission and multi-channel force measurement [28,29]. Graichen and Bergmann described a fully implantable four-channel telemetry system capable of measuring three-dimensional joint forces using strain gauges embedded within a hermetically sealed prosthesis, enabling long-term in vivo measurements without percutaneous leads, with a new example depicted in Figure 3 [9]. These designs eliminated external wiring, allowed more natural patient movement, and enabled repeated measurements across a wider spectrum of activities, including higher-demand tasks and perturbation scenarios [28,29]. Investigations during this period also began to address specific biomechanical questions, such as the influence of gait phases (e.g., heel strike), instability events, and task-specific variations on joint loading [30]. By the mid-1990s, study designs became increasingly hypothesis-driven, moving beyond feasibility demonstrations toward detailed characterization of loading under controlled functional conditions. For example, investigations of stair ascent and descent employed instrumented implants with multi-channel telemetry combined with video synchronization to quantify joint forces, bending moments, and torsional loads, demonstrating that the direction and torque of loading may be critical determinants of implant fixation, rather than force magnitude alone [31]. Similarly, studies evaluating interventions such as ischial weight-bearing orthoses illustrated how telemetry could be used not only to measure loads but also to experimentally test therapeutic concepts, showing that orthotic designs reduced joint forces only modestly and highlighting the complexity of load redistribution in vivo [32]. Parallel studies examining load carriage combined modelling with telemetry measures to evaluate how external loads alter joint forces, illustrating early integration between direct experimental measurement with biomechanical modelling approaches [33].

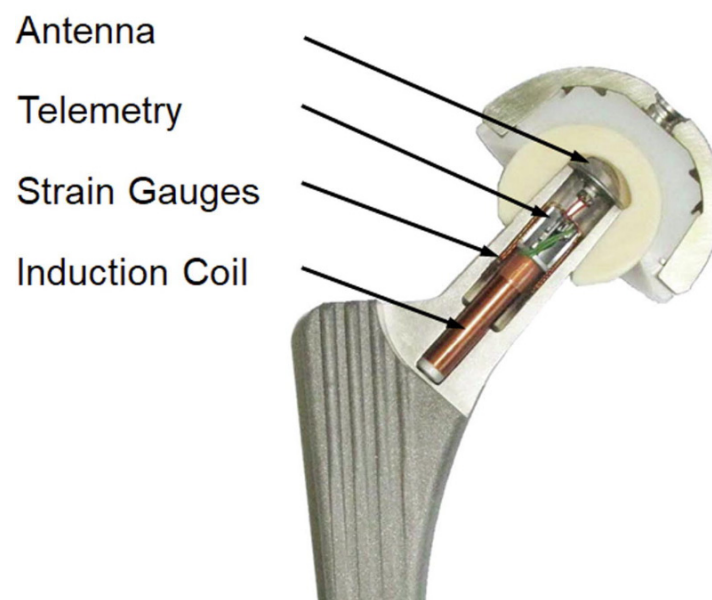


Figure 3. The latest generation of instrumented implants, the Hip III prosthesis, capable of monitoring three moments and three force components utilizing nine channels. Other prostheses include temperature or pressure sensors in the shaft as well. Used from www.OrthoLoad.com with permission for non-commercial academic publication. Data © Julius Wolff Institute/OrthoLoad [34].

Clinical force measurements were reported in small cohorts. Kotzar et al. presented telemeterized force data from two patients following total hip arthroplasty, demonstrating peak loads of approximately 2.7 times body weight during gait and up to 5.5 times body weight during episodes of instability in single-leg stance [35]. Importantly, the authors

noted that measured forces during activities of daily living were generally lower than those predicted by analytical biomechanical models, highlighting early discrepancies between computational estimates and direct measurements.

Several investigations during this period focused on contact pressures rather than resultant forces. Strickland and colleagues reported acetabular contact pressures during early rehabilitation in a pressure-instrumented hemiarthroplasty, demonstrating that isometric hip extension could generate higher pressures than normal gait and that clinical indicators such as pain or range of motion did not reliably reflect mechanical loading [36]. These findings challenged prevailing assumptions regarding the relative safety of commonly prescribed rehabilitation activities.

Studies from the Massachusetts General Hospital group further explored pressure distribution across functional tasks. McGibbon et al. measured acetabular pressures during cane-assisted and load-carrying walking over a two-year period in a single subject, demonstrating that carrying loads ipsilateral to the operated hip increased contact pressures and that contralateral cane use could reduce ipsilateral joint loading while increasing contralateral stresses [37]. Such observations provided early quantitative evidence of activity-dependent modulation of hip joint loading.

The relationship between direct measurements and biomechanical modelling was examined by Park et al., who combined pressure telemetry from instrumented hemiarthroplasty with motion analysis to investigate muscle co-contraction [38]. Their findings indicated that muscle co-contraction contributes substantially to hip joint loading and underscoring the limitations of indirect biomechanical estimation methods [38].

Early attempts to validate biomechanical modelling against in vivo measurements were also reported. Stansfield and colleagues examined the relationship between external gait parameters and internal hip loading, highlighting the challenges of accurately estimating joint forces from kinematics alone and reinforcing the importance of direct telemetry measurements for model validation [39].

Collectively, the pre-2000 literature provided the conceptual and technological foundation for modern instrumented implant research, establishing the critical role of direct in vivo measurement in advancing the understanding of hip biomechanics relevant to functional recovery and activity participation following THA.

Expansion of in vivo telemetry (2000–2010): clinically relevant loading patterns and validation of indirect methods.

During the early 2000s, research using instrumented hip implants transitioned from isolated feasibility reports to more systematic datasets that provided clinically meaningful insight into hip loading during everyday activities. Studies from the Berlin research group established reference values for hip contact forces measured in vivo, demonstrating peak loads of approximately 2–3 times body weight during level walking and slightly higher forces during stair negotiation, with considerable inter-individual variability [11]. These findings reinforced the central role of routine activities as the primary contributors to cumulative implant loading. Parallel work explored the relationship between measured forces and biomechanical modelling. Comparisons between patient-specific musculoskeletal simulations and telemetry data demonstrated reasonable agreement in overall loading patterns but also highlighted notable discrepancies, emphasizing that indirect methods should be interpreted cautiously when used to estimate joint loading [40]. Continued work on telemeterized implants during this period expanded the characterization of load patterns across a wider range of functional conditions and contributed to the development of standardized loading scenarios for implant testing and simulation, bridging early feasibility studies with later large telemetry datasets [41]. Furthermore, measurements during stumbling episodes revealed peak forces substantially exceeding those observed during normal gait,

highlighting the potential biomechanical relevance of unexpected perturbations rather than routine activity alone [42]. Beyond force magnitude, this period also introduced measurements of implant temperature during prolonged activity, demonstrating modest increases during extended walking and suggesting that friction-related effects may vary depending on activity characteristics and bearing materials [43]. Although the clinical implications remain uncertain, these findings contributed to a deeper understanding of implant behaviour under sustained loading conditions.

Heller and colleagues further extended telemetry research by integrating instrumented implant measurements with subject-specific musculoskeletal modelling to characterize internal femoral loading during walking and stair climbing. Their results showed that axial compression represents the dominant loading component, whereas bending moments vary along the femoral shaft and are influenced by implant alignment [44]. This work represented an important step toward linking in vivo measurements with biomechanical modelling, advancing understanding of how surgical parameters influence functional loading following THA.

Collectively, studies from 2000 to 2010 provided the first robust clinical framework for interpreting in vivo hip joint loading. These investigations validated the general mechanical safety of routine activities while emphasizing considerable variability between patients and highlighting the potential importance of occasional high-load events (Figure 4). These findings from this period laid the groundwork for subsequent investigations exploring activity-specific loading patterns and their implications for postoperative counselling and return-to-play recommendations [45].

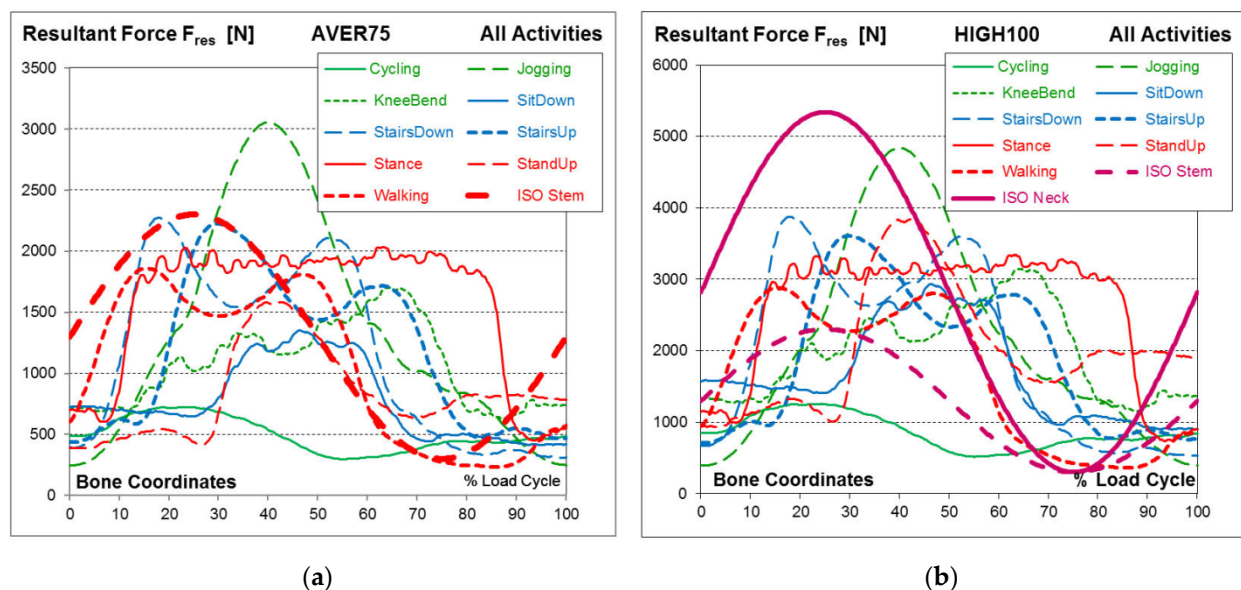


Figure 4. Typical forces diagram acquired from instrumented-implant studies: (a) average forces in subjects with average bodies; (b) high forces in subjects with high body weight. The resultant forces during nine activities of daily living are compared to the ISO forces, defined for endurance test on the neck of hip implants. Used from www.OrthoLoad.com with permission for non-commercial academic publication. Data © Julius Wolff Institute/OrthoLoad [34,46].

Post-2010 evidence: clinically relevant in vivo loading patterns from instrumented hip implants.

3.1. Activities of Daily Living and “Reference” Loads

From 2010 onward, instrumented implant cohorts were increasingly used to move beyond the analysis of isolated activities and define clinically interpretable reference loading

spectra for THA. In a standardized-load analysis of 10 subjects, Bergmann and colleagues quantified typical magnitudes and directions of hip contact forces during common and physically demanding activities of daily living, with the aim of supporting more realistic preclinical implant testing and improving interpretation of in vivo biomechanics, particularly in younger and more physically active THA populations [46]. Complementing this work, comparative analyses across instrumented implants demonstrated that level walking produces distinct load profiles across hip, knee, and spinal implants, reinforcing the need to interpret “activity safety” in joint-specific terms rather than extrapolating findings from one anatomic site to another [46].

3.2. Rehabilitation and Physiotherapy: Loads May Exceed Walking in Selected Tasks

A consistent and clinically relevant observation emerging from post-2010 telemetry studies is that some supervised rehabilitation exercises may be mechanically demanding and occasionally approach or exceed the loads observed during walking. In a cohort of six patients, Schwachmeyer et al. quantified hip contact forces and moments across 13 common prescribed postoperative physiotherapy exercises including variations in pelvic lifting (bridging), hip abduction (isometric and active), isometric straight and flexed knee and pelvic tilt. Common weight-bearing exercises like the lifting pelvis utilizing only the operated limb generated the highest peaks (up to 441% body weight), exceeding walking loads by 166%. This suggests important information as many surgeons prescribe this exercise during the early post-operative period while not allowing for full-weight-bearing walking, while the activity is being performed during bed-pan use, attributed to the muscle co-contraction effect during unilateral limb exercises [47]. In contrast, long-lever-arm and dynamic exercises tended to produce loads approximately half those observed during walking loads but high torsional moments, while isometric exercises of the hip and knee demonstrated substantial variability depending on contraction intensity [48]. These findings are directly relevant for postoperative counselling, indicating that physiotherapy exercises cannot universally be considered low-loading activities, and that exercise selection and execution intensity significantly influence implant loading.

3.3. Forward-Bent Postures and Lifting: Hip Loads Rise with Flexion and Are Technique-Sensitive

While most telemetry studies focus on gait and sport activities, forward-bent posture such as stooping, lifting and common household or occupational tasks represent an important but often overlooked source of mechanical exposure. Using instrumented hip endoprosthesis data (and, in a parallel cohort, instrumented spinal implants), Damm et al. showed that hip resultant forces increase almost continuously with trunk inclination, with peak hip forces reported in a range of approximately 360–540% of body weight (BW) depending on task and posture [48]. Importantly, lifting technique redistributed loading between the hip and spine. Bent-knee lifting tended to reduce hip joint loads while slightly increasing spine loads, whereas straight-knee lifting tended to increase hip loads while decreasing spine loads, challenging simplified suggestions that techniques beneficial for the spine are necessarily beneficial for the hip joint [48].

3.4. Gait Style Modification: Do Kinematic Changes Equal Kinetic Changes?

Proximal mechanics are also sensitive to how an activity is executed, not only to the activity itself. Using instrumented THA data to validate musculoskeletal simulations, Angelini et al. tested different arm-swing amplitudes and arm positions during level walking and found that altering arm swing influenced upper-body and free-moment metrics but had minimal effect on hip joint reaction forces. This suggests that many gait “style” modifications may not meaningfully unload the hip despite visible kinematic changes [49]. In other words, not every “gait tweak” results in reduced hip loading. These

findings support focusing clinical counselling on activity dose, intensity and task selection, rather than expecting arm-position strategies to substantially reduce hip forces.

3.5. Muscle Status and Early Postoperative Biomechanics

Beyond activity-related effects, studies examining periarticular muscle condition demonstrate that patient-specific factors significantly influence in vivo loading. Imaging-based analyses in patients with instrumented implants showed that early postoperative deterioration of hip abductor musculature was associated with higher joint contact forces during activities of daily living, suggesting that muscle integrity represents a key determinant of mechanical exposure after THA [50]. Another cohort study examined the relationship between muscle status and fatty degeneration of tensor fascia lata and gluteal muscles with joint loading over time, reporting increased joint loading associated with muscle atrophy and documenting postoperative changes in loading patterns. These findings support the clinical intuition that rehabilitation and recovery of muscle function are not only functional goals but also important biomechanical modifiers of implant loading [51]. Collectively, these findings provide mechanistic support for targeted rehabilitation strategies aiming at optimizing load distribution following THA.

3.6. Assistive Devices: Forearm Crutches Reduce Hip Loads Modestly—And Mainly Early

In vivo measurements during ambulation with forearm crutches showed only modest average reductions in hip joint loading compared with walking without crutches. Across seven patients, peak hip contact force decreased by approximately ~12–17% depending on gait pattern used (3-, 4-, or 2-point gait), with similar modest reductions in bending moment and torsion [52]. Notably, reductions greater than >20% were primarily observed during the first four postoperative weeks, with declining crutch force use over time. These observations support the clinical interpretation that crutches may not substantially unload the hip beyond the early recovery phase, and that patient technique and adherence play an important role in determining their effectiveness [52].

3.7. Footwear as a Modifiable Factor Influencing Hip Loading During Walking

Using instrumented total hip prostheses, Palmowski et al. showed that shoe type can influence in vivo hip joint loading during walking [53]. Compared with barefoot walking, most conventional footwear increased resultant contact forces and bending moments at heel strike, with the largest increases observed in everyday and dress-type shoes. In contrast, a minimalist “barefoot shoe” showed lower peak values on hip joint loading [54]. Torsional loads were also higher with several shoe types of footwear, especially stiffed sole and men’s shoes, suggesting that footwear selection may alter mechanical demands at the implant–bone interface even during routine gait, with barefoot shoes again showing minimal values [53]. These findings indicate that footwear represents a simple and potentially modifiable factor influencing hip loading after THA, lubrication film, implant stability and bearing surface wear.

3.8. Friction and Cup Stability: Sustained Loading and Specific Activities Increase Risk-Relevant Moments

A major maturation of the field after 2010 was the shift from focusing solely on force magnitude to examining friction-related moments, which are clinically relevant to acetabular fixation and loosening mechanisms. Direct in vivo measurements during walking demonstrated peak contact forces of approximately 248% of bodyweight and measurable friction moments. Importantly, friction metrics varied substantially between individuals and across phases of gait cycle, emphasizing that patient-specific factors and lubrication state may influence implant-related risk [54]. Another study presenting longitudinal measurements between 3 and 12 months postoperatively showed that friction-related pa-

rameters can change over time even when resultant contact forces remain relatively stable, supporting the concept that implant “run-in” phenomena and postoperative recovery may modify tribological behaviour [55]. Clinically, one of the most important observations is that friction moments can increase sharply under specific conditions. After a short rest, initiation of walking was associated with markedly higher friction moments in the first step with increases of approximately 32% to 143% on average, with individual peaks up to 621%, despite no increase in contact force. This finding suggests a lubrication-dependent mechanism rather than purely force dependence phenomenon [56].

3.9. Activity-Specific Loading Relevant to Rehabilitation and Return to Activity

At the same time, other research groups have focused on activity-specific loading patterns relevant to rehabilitation and return to activity decisions. In a large activity screening study including more than 1400 activities and approximately 33,000 measurements across nine subjects, numerous activities generated friction moments at or above a proposed “critical” threshold for cup fixation stability [57]. The highest peaks were reported during tasks characterized by sustained high loading with limited joint motion such as prolonged or unstable one-legged stance variations, stretching exercises, whole-body vibration training, running after stance and breast-stroke swimming [57]. Direct measurements during cycling demonstrated that hip joint loads increase approximately linearly with power output and are influenced by cadence and saddle height, providing quantitative guidance for exercise prescription following THA, with 60 rates per minute and high saddle height providing the lowest joint loads [58]. Comparative analyses across hip, knee, and spinal implants further contextualized hip loading within whole-body biomechanics and reinforced walking as a key reference activity for interpreting mechanical exposure [59]. Investigations of tensor fascia latae and gluteal muscle status also demonstrated that periarticular muscle atrophy is associated with increased joint loading both in the early postoperative period and long term, underscoring the importance of neuromuscular recovery in modulating mechanical demand [51].

Collectively, these findings are directly relevant to RTP counselling, as they indicate that risk-relevant mechanical exposure may arise from sustained or constrained-loading tasks rather than solely from high-impact sport.

3.10. Water- and Swim-Based Activity: Generally Lower Forces than Land, but Not Uniformly “Low Load”

Aquatic therapy is commonly recommended after THA. However, in vivo telemetry data demonstrate that loading in water depends strongly on the type and the intensity of the activity performed. In instrumented hip and knee implant recipients (including six hip patients), aquatic exercises (categorized in non-weight bearing, weight bearing and dynamic) produced hip joint forces ranging approximately 32% to 396% of body weight, with meaningful reductions of 36–55% compared with equivalent land-based activities for many weight bearing and dynamic movements. However, drag-intensive non-weight-bearing movements performed as higher velocities or resistive fins substantially increased joint forces compared to land base equivalents [60]. For swimming specifically, in vivo measurements showed median maximal hip forces during breaststroke swimming in the range of approximately 157% to 193% body weight, increasing with swimming speed. Crawl kick produced higher hip forces and moments than breaststroke kicking, indicating that swimming technique significantly influences joint loading [61]. Clinically, these data support recommending water-based exercise as a load-modulatable rehabilitation modality, suitable for graded progression toward RTP when technique and intensity are appropriately controlled.

3.11. Nordic Walking (Structured, Coachable): Loads $\approx$ Ordinary Walking

In vivo telemetry suggests Nordic walking can generally be considered biomechanically comparable to ordinary walking, rather than representing a substantially higher-load activity. In six instrumented-THA patients, hip joint loads during Nordic walking showed the typical double-peak pattern and were comparable to ordinary walking under both level and incline conditions [62]. Technique influenced certain aspects of the loading pattern. Double-poling slightly reduced resultant force and bending moment during contralateral heel strike, whereas the diagonal technique could increase the second peak during uphill walking. However, the absolute peak force remained similar to that observed during ordinary walking [62].

3.12. Manual Handling and Lifting Mechanics

Instrumented implant analyses of standardized lifting tasks provide valuable insight into loading during activities relevant to occupational return. In telemetric measurements of a 10 kg lifting task, different lifting techniques (e.g., stoop versus squat) resulted in similar magnitudes of hip contact force but altered the direction of the resultant force vector, indicating that technique influences load orientation rather than overall magnitude [63]. This observation suggests that mechanical risk during lifting may relate not only to force magnitude but also to the direction of the resultant vector and associated joint moments, underscoring the complexity of translating generic ergonomic lifting advice into implant-specific recommendations [64]. Using instrumented implants measuring hip, knee, and spinal loads during stoop and squat lifting, Brandl et al. evaluated whether commonly used ergonomic risk assessment tools (OWAS and REBA) accurately reflect actual joint loading. Hip contact forces reached approximately three times body weight during lifting, with higher torsional moments observed particularly during squat techniques [64]. While OWAS and REBA action levels were able to distinguish between different loading conditions, similar risk categories did not correspond to equivalent in vivo loads, indicating that observational ergonomic scores only partially reflect true mechanical exposure [64]. These findings suggest that lifting technique influences hip loading characteristics and highlight the limitations of relying solely on observational risk tools to infer joint mechanics after THA.

3.13. Gym-Machine Training: Mostly $\leq$ Walking, Except Ipsilateral Single-Leg Rope-Pull Variants

The first telemetry study to quantify hip loads across common gym machines (leg curl, leg extension, leg press, rope pull) found that, across 23 load conditions in 7 patients measured approximately 17 months after THA, most configurations produced lower or similar resultant forces and moments compared with treadmill walking at 4 km/h (median walking peaks $\sim 303\%$ BW) [65]. A consistent exception was rope-pull exercises performed in ipsilateral monopod stance, which tended to increase resultant force and bending moment, supporting a pragmatic rehabilitation message: machines can be “low-impact”, but single-leg or ipsilateral stance variants require supervision and careful dose control [65]. Complementing the gym-machine data, in vivo telemetry has also been applied to gymnastics and aerobics-type exercises, providing direct evidence for a class of RTP-relevant “fitness” activities that are commonly performed but historically evaluated using indirect assumptions [66]. Gym based classes may therefore be appropriate for later-phase conditioning, although single-leg stretching tasks, higher-tension resistance bands, and step-board aerobics may require phase-specific restriction and careful technique supervision.

3.14. Whole-Body Vibration (WBV): Forces Remain Well Below Walking Despite Variable Damping

WBV training has also been benchmarked against walking using instrumented hip implants. Across different standing positions and vibration platforms, total hip contact

forces during WBV consistently remained below walking peaks, reported as less than approximately 79% of walking forces [67]. At the same time, vibration-induced dynamic force components demonstrated substantial high inter-individual variability and strong damping between the knee and hip joints, indicating that platform cannot reliably be used as a proxy for internal hip loading [67]. Overall, WBV appears to represent relatively low mechanically exposure compared to walking from a hip-load perspective, although dosing cannot be inferred reliably from platform settings alone.

3.15. Sport-Relevant Tasks: Simulator Evidence for Cross-Country Skiing Suggests Loads near Walking—Except in Unilateral Phases

Telemetry has begun to address sport-specific loading more directly. In a simulator study of cross-country skiing techniques, peak loads were generally comparable to or lower than those observed during walking, although technique-dependent differences were identified. Diagonal poling with foot lift produced a median peak resultant force of approximately 315% body weight, whereas other variants ranged broadly but typically remained within a “walking-adjacent” envelope [68]. Bending moments during diagonal techniques could slightly exceed walking values, and occasional outliers were observed [68]. The authors’ clinical interpretation was pragmatic: double or diagonal poling techniques may be acceptable in later stages of rehabilitation, whereas prolonged unilateral standing phases should be minimized, particularly in less experienced patients, and recommendations should account for patient experience and bone quality [68].

3.16. Patient Factors and Expectations: Younger Working-Age Patients Demonstrate Higher Loads in Recommended Activities

A clinically oriented analysis explicitly linked patient expectations and age category to measured loading. In “working age” (<60 years) versus “retirement age” (>60 years) THA patients, recommended activities generated higher hip contact loads in the working-age group. Furthermore, certain activities—including those perceived as “low risk”—produced substantial forces and torques. The authors cautioned that increasing expectations for rapid return to work and sport may expose implants to higher loads than commonly assumed, emphasizing the need for structured counselling toward lower-impact activity profiles when appropriate [69].

3.17. Indirect Prediction and Planning: External Measures as Proxies for In Vivo Loading

Several studies addressed the translational challenge of estimating in vivo joint loading in the absence of implant telemetry. A direct comparison of radiograph-based biomechanical models with instrumented implant measurements found that some simplified models approximate the magnitude of the resultant hip force reasonably well, whereas estimates of force orientation were highly variable and appeared more dependent on model assumptions than on patient-specific factors [70]. More recently, a gait-focused analysis in eight patients with instrumented THA implants demonstrated that ground reaction forces (GRFs) time-series data—alone or combined with external hip moments and lean muscle volume—can be used to predict certain aspects of in vivo hip contact force impulse during gait. These findings support the potential use of clinically accessible proxies for estimating implant loading, while telemetry remains the benchmark for validation [71].

Further studies evaluating whether GRFs and external joint moments can predict in vivo hip contact forces demonstrated that external measures alone are insufficient, but predictive value may improve when combined with muscle metrics or joint moment data, illustrating progress toward noninvasive monitoring strategies [72]. Together, these contemporary investigations reflect a broader shift toward integrating direct measurements with biomechanical modelling, rehabilitation science, and clinical decision-making, advancing

understanding of how activity patterns, patient characteristics, and implant mechanics interact in the modern THA population.

3.18. Thermal Environment and Implant Orientation

Beyond pure mechanical measurements, combined in vivo and in silico investigations have evaluated determinants of friction-related temperature increases within hip implants. In a large retrospective dataset comprising approximately 38,000 activity trials from 10 subjects with instrumented THA implants, cup orientation was associated with joint kinematics and friction-related temperature increases. Interestingly, temperature changes were not primarily explained by contact-force magnitude alone, suggesting that tribological risk may be more sensitive to lubrication conditions and kinematics than to peak force levels [15]. Additional analyses of in vivo loading further emphasized the interaction between joint mechanics and implant tribology, demonstrating that variations in loading conditions and activity patterns influence frictional behaviour and mechanical environment of the implant. These findings reinforce the concept that mechanical exposure of the hip joint after THA cannot be adequately characterized by peak force magnitude alone [15].

4. Discussion

4.1. What Instrumented Hip Implants Add to the RTP Debate

The present scoping review demonstrates that instrumented hip implants shift the discussion around return to play (RTP) after THA from one largely based on expert opinion to one grounded in direct in vivo biomechanical evidence. Instrumented hip implants uniquely address this gap by providing in vivo measurements of joint contact forces, moments, frictional behaviour, and activity-dependent loading patterns, enabling RTP guidance to be grounded in measured mechanical exposure rather than in assumptions derived solely from perceived impact alone [11]. Across decades of telemetry research, a consistent observation emerges: routine activities such as walking provide a reproducible reference envelope for hip joint loading, typically in the range of approximately two to three times body weight, albeit with substantial inter-individual variability [11]. Activity monitoring studies demonstrated that patients spend the majority of their time performing low-load activities such as sitting and standing, while walking contributes the largest proportion of cyclic mechanical loading experienced by the implant, providing more realistic assumptions regarding implant use in daily life [73]. This reference frame is clinically meaningful because many activities traditionally considered “safe” including cycling, aquatic exercise, Nordic walking, and several gym-based exercises, frequently fall within or near this envelope when performed in a controlled manner [58,60,62,65]. However, telemetry also reveals that mechanical exposure cannot be inferred solely from activity labels. Certain rehabilitation exercises, lifting tasks, and sustained postures may produce loads equal to or exceeding those encountered during walking [47,48,64]. Thus, instrumented implant studies demonstrate that “low impact” activities necessary correspond to low mechanical exposure is not always valid.

4.2. Reframing Mechanical Risk: Beyond Peak Force

A central insight from instrumented implant research is that mechanical risk cannot be inferred solely from peak contact force magnitude. Frictional moments at the acetabular interface—particularly during sustained loading, constrained positions, or initiation of movement after rest—may be more relevant to fixation and tribological behaviour than force magnitude alone [15,54–57]. Activities such as prolonged single-leg stance, stretching, or certain swimming patterns can generate friction moments approaching proposed critical thresholds despite only moderate joint contact forces [57]. Similarly, load direction and

torsional components vary with technique, as demonstrated in lifting and manual handling tasks, where similar force magnitudes were accompanied by different vector orientations and joint moments [63,64]. These findings suggest that RTP counselling should consider not only which activities are undertaken but also how they are executed.

4.3. Rehabilitation and Patient Factors as Major Determinants

Telemetry evidence highlights that postoperative rehabilitation is a major determinant of joint loading. Weight-bearing physiotherapy exercises can produce loads exceeding walking, and muscle impairment—particularly gluteal or abductor insufficiency—has been associated with increased joint contact forces early after THA [47,50,51]. These observations reinforce the importance of targeted strengthening and neuromuscular rehabilitation as key biomechanical modifiers of joint loading, rather than viewing rehabilitation solely as a means to restore functional performance. Unexpected perturbations, such as stumbling, generate some of the highest recorded forces, emphasizing the role of balance training and fall prevention strategies when evaluating RTP readiness [42]. Moreover, younger or highly active patients may expose implants to higher even loads during recommended activities, underscoring the need for individualized RTP counselling [69].

4.4. Modifiable Factors Influencing Loading

Several modifiable factors influence hip loading during everyday activities. Forward trunk inclination substantially increases joint forces, while lifting technique redistributes loads between the hip and spine [48]. Footwear can alter loading at heel strike, with certain shoe types increasing joint forces and moments compared with barefoot walking [53]. Assistive devices such as crutches provide only modest mechanical unloading beyond early postoperative period, highlighting the importance of patient technique and adherence when such devices are prescribed [52]. Collectively, these findings suggest that RTP guidance should incorporate practical advice regarding posture, equipment, and movement technique in addition to activity selection.

4.5. Role and Limitations of Indirect Biomechanical Approaches

While musculoskeletal modelling and gait-analysis can approximate loading magnitude, these methods remain sensitive to assumptions and may not accurately capture force orientation or frictional behaviour or individual muscle activation patterns [70–72]. Telemetry therefore remains the reference standard for understanding true joint mechanics, although integration with modelling approaches offers a promising pathway toward more scalable and clinically applicable tools estimating implant loading. How telemetry evidence informs the RTP algorithm

(1) Risk stratification

Higher caution is warranted in patients with:

- Abductor weakness or muscle atrophy [50,51]
- Balance deficits (stumbling) or fall risk [42]
- High activity expectations or rapid escalation of mechanical load [69]

(2) Use walking as reference exposure

Progress activities relative to the joint load observed during walking ($\sim 2\text{--}3 \times \text{BW}$), which serves as a clinically meaningful reference for mechanical exposure [11]. Certain everyday activities traditionally considered safe, like unilateral pelvic lifting (bridges) for bed-pan use, should be treated with caution as they could cause excessive loads during the early post-op phase [69].

(3) Progress by mechanical principles

- Prioritize restoration of strength, motor control, and balance before returning to sport-specific activity [42,49,50]
 - Introduce load-modulatable activities such as cycling, aquatic exercise, Nordic walking, gym machines [58,60,62,65]
 - Avoid prolonged static loading and constrained positions during early rehabilitation [57]
 - Carefully monitor modifiable factors and technique during lifting and resistance training exercises [48,65]
- (4) Categorize activities based on mechanical phenotype
- Early phase: load-modulatable cyclic activities: Activities with controllable intensity and loads $\leq$ walking should be prioritized, such as cycling, aquatic exercise, Nordic walking, and most gym-machine exercises [58,60,62,65].
 - Intermediate phase: walking-adjacent activities: Activities producing loads comparable to walking can be introduced once baseline tolerance is achieved, including selected aerobics, skiing-type movements, and structured conditioning exercises [66,68]
 - Advanced phase: technique- and torsion-sensitive activities: Activities involving trunk flexion, lifting, unilateral stance, or altered mechanics should be introduced cautiously, as they modify load direction, torsion, and magnitude rather than simply increasing peak force [48,63,64].
 - High-risk scenarios (delayed or restricted): Activities associated with perturbations, start-stop loading, or sustained static loading should be delayed or selectively restricted, as they generate extreme forces or frictional moments [42,56,57]
- (5) Individualize final RTP decision: Final RTP clearance should integrate patient-specific factors, activity mechanics, and functional recovery rather than relying solely on traditional sport classifications. RTP after THA should be guided by walking-referenced mechanical exposure, progressed through load-modulatable activities, and individualized based on patient factors, technique, and activity-specific loading characteristics [18,46,69].

4.6. Why Controversy Persists

Despite decades of telemetry research, definitive sport-specific recommendations remain limited by small cohorts, heterogeneous implant designs, and incomplete coverage of high-demand athletic activities. Furthermore, risk mechanisms appear multifactorial, encompassing load magnitude, frictional behaviour, cumulative exposure, and patient specific factors. Importantly, biomechanical parameters measured using instrumented implants have not yet been directly correlated with clinical outcomes, such as implant survivorship, loosening, wear, or revision rates [15,57]. This complexity explains the persistent variation in clinical practice and supports shared decision-making rather than rigid activity prohibitions.

4.7. Clinical Implications

Instrumented implant evidence supports a shift from prescriptive activity bans toward individualized load management strategies. RTP after THA should be viewed as a continuum that emphasizes high-quality rehabilitation, gradual exposure to mechanical load, and patient education regarding modifiable risk factors. Importantly, many recreational activities appear biomechanically acceptable when performed with appropriate technique and gradual progression, whereas less recognized exposures—such as demanding rehabilitation tasks or sustained postures—may represent overlooked sources of mechanical stress.

Limitations

This review is limited by the small, highly selected cohorts implanted with specialized research prostheses, which may restrict generalizability to broader THA populations. Unfortunately, we managed to access only two databases; however, reference chasing ensured that we have included all relevant studies. Substantial heterogeneity in implant design and measurement techniques exists during the early studies; later studies, however, by the Bergman group, are standardized. Activity protocols also show great heterogeneity precluding quantitative synthesis. Most studies evaluated controlled tasks rather than unrestricted sport participation, and high-demand activities remain underrepresented in the telemetry literature. Finally, telemetry quantifies mechanical exposure but does not define clinical failure thresholds, and long-term cumulative loading data are limited.

5. Conclusions

Across the available evidence, joint loading is highly activity- and patient-specific, with many recreational activities falling within the safe range of daily functional loading. At the same time, telemetry demonstrates that the mechanical environment is influenced by factors beyond peak force, including frictional behaviour, load direction, and neuromuscular status. Our findings suggest that routine walking serves as a reproducible reference loading envelope, revealing that many load-modulatable sports fall within this range, while certain supervised rehabilitation exercises and forward-bent postures frequently exceed it. Future research should expand in vivo telemetry datasets across a broader spectrum of sports and functional tasks, study how parameters can influence the mechanical environment within a certain task and integrate telemetry with biomechanical modelling in order to refine evidence-based RTP guidance for physically active patients after THA.

Author Contributions: Conceptualization: V.G.; methodology: I.T. and K.K.; writing—original draft: V.G., P.A. and M.K.; writing—review and editing: V.G., S.A.X., C.T., N.I.L. and R.G.; supervision: A.P., project administration: V.G.; investigation: V.G., I.T., P.A. and M.K.; formal analysis: V.G., K.K. and I.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created during this scoping review. Data sharing is not applicable.

Acknowledgments: Vasileios Giannatos would like to acknowledge the support and academic influence of the JEO-ESSKA Research Fellowship. Special thanks are extended to Laura De Girolamo for her mentorship, which significantly contributed to the development of critical research skills, the expansion of academic perspectives, and the conception of the author's first scoping review.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

RTP	Return to play
THA	Total hip arthroplasty
RTS	Return to sport
TKA	Total knee arthroplasty
OSF	Open science framework
PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews

PCC	Population–Concept–Context
BW	Body weight
WBV	Whole-body vibration

Appendix A

Table A1. Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist.

SECTION	ITEM	PRISMA-ScR CHECKLIST ITEM	REPORTED ON PAGE
TITLE			
Title	1	Identify the report as a scoping review.	Line 3
ABSTRACT			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	Page 1, 2
INTRODUCTION (Section 1)			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	Lines 47–121
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	Lines 123–129
METHODS (Section 2)			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a web address); and if available, provide registration information, including the registration number.	Lines 133–136
Eligibility criteria (Section 2.2)	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	Lines 138–145
Information sources	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	Lines 154–158
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	Lines 156, 776–790
Selection of sources of evidence	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	Lines 138–152
Data charting process	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	Lines 160–162
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	Lines 162–164
Critical appraisal of individual sources of evidence	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	Lines 164–167
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	Lines 160–162
RESULTS (Section 3)			
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	Lines 169–187
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	Lines 169–187
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Lines 792–797
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	Lines 189–589
DISCUSSION (Section 4)			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	Lines 591–717
Limitations (Section Limitations)	20	Discuss the limitations of the scoping review process.	Lines 719–730
Conclusions (Section 5)	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	Lines 732–744
FUNDING			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	Lines 753

Appendix B

The PubMed advanced search query was:

("Arthroplasty, Replacement, Hip"[Mesh] OR "Hip Prosthesis"[Mesh] OR "total hip replacement"[Text Word] OR "total hip arthroplasty"[Text Word] OR "hip implant*"[Text Word] OR "hip prosthes*"[Text Word] OR "THA"[Text Word] OR "THR"[Text Word]) AND (("in vivo"[Text Word] AND ("load*"[Text Word] OR "force*"[Text Word] OR "moment*"[Text Word] OR "friction"[Text Word] OR "pressure"[Text Word] OR "temperature"[Text Word] OR "measure*"[Text Word])) OR "contact force*"[Text Word] OR "joint load*"[Text Word] OR "instrumented"[Text Word] OR "telemetry"[Text Word] OR "telemetric"[Text Word] OR "telemeterized"[Text Word] OR "orthoload"[Text Word] OR "smart implant*"[Text Word] OR "sensor"[Text Word]).

The Scopus search query was adapted as follows: TITLE-ABS-KEY (("total hip replacement" OR "total hip arthroplasty" OR "hip prosthesis" OR "hip implant*" OR "THA" OR "THR") AND (("in vivo" AND (load* OR force* OR moment* OR measure* OR friction OR temperature)) OR "contact force*" OR "joint load*" OR "instrumented implant*" OR "instrumented prosthes*" OR "telemetr*" OR "orthoload")).

Appendix C

Table A2. Data extraction from the included 50 studies. Abbreviations included BW: body weight, RTP: return to play, ADL: activities of daily life, and THA: total hip arthroplasty. Numerical outcomes for the corresponding activity are presented as percentage of the body weight where available, as it is commonly used as a reference point.

Study	Year	Sample Size	Activity	Telemetry Implant Model	Key Finding	Numerical Outcomes (% of BW)	RTP Relevance	Notes
Rydell [68]	1966	1	Walking, stance	Early telemetry	First direct in vivo quantification of hip joint forces, demonstrating that physiological loads during gait substantially exceed body weight even in normal activities	Walking approximately 200–300% BW	Establishes the fundamental biomechanical baseline for all RTP considerations	First strain-gauge prosthesis, limited accuracy but historically critical
English & Kilvington [41]	1979	2	Walking, stance	Early telemetry	Confirmed reproducibility of gait-related hip loading, reinforcing that peak forces consistently exceed 2–3× body weight	~290–330% BW during walking	Supports use of walking as a reproducible reference activity for RTP progression	Early validation of telemetry concept
Davy et al. [40]	1988	1	Standing, walking, stairs	Early telemetry	Demonstrated that even low-demand ADLs produce substantial hip joint forces, challenging assumptions of "safe" low-load activities	Standing ~100% BW, walking ~260–280% BW, stairs ~260% BW	Highlights that RTP risk is not limited to sport but also includes daily activities	Single-case study but foundational
Bergmann et al. [8]	1989	1	Walking, physiotherapy	HIP II	Showed that walking produces consistent peak loads around 3× BW, while certain resisted rehabilitation exercises generate comparable forces	Walking ~300% BW, exercises up to ~250% BW	Defines early rehabilitation loading envelope relative to walking	Demonstrated partial unloading effect of crutches
Hodge et al. [53]	1989	1	ADLs	Early telemetry	Identified that specific ADLs (e.g., chair rise) can generate joint pressures comparable to or exceeding walking loads	Pressure-based (no %BW)	Emphasizes that non-sport activities may represent hidden high-load exposures	Focused on pressure rather than force
Kotzar et al. [57]	1991	2	Gait, stance	HIP II	Reported large variability in hip forces, with instability events producing extreme peaks well beyond normal gait values	Walking ~210–270% BW, instability up to ~550% BW	Identifies instability and perturbations as high-risk RTP scenarios	One of first studies demonstrating extreme peaks
Graichen & Bergmann [46]	1991	2–3	ADLs	HIP II	Established feasibility of multi-channel telemetry, enabling measurement of multidirectional forces in vivo	Not reported	Foundation for all modern RTP biomechanical evidence	Technical milestone

Table A2. Cont.

Study	Year	Sample Size	Activity	Telemetry Implant Model	Key Finding	Numerical Outcomes (% of BW)	RTP Relevance	Notes
Strickland et al. [71]	1992	1	Rehabilitation	HIP II	Demonstrated that early physiotherapy exercises may generate loads similar to or exceeding walking, depending on muscle activation intensity	Walking 180–330% BW, exercises up to ~200% BW	Suggests early RTP progression must consider exercise intensity, not just activity type	Isometric exercises highly variable
Givens-Heiss et al. [45]	1992	1	Rehabilitation	HIP II	Shown that muscle force generation and contraction velocity significantly influence hip joint loading during rehab	Not standardized	Supports controlled, progressive rehabilitation strategies for RTP	Highlights neuromuscular influence
Bergmann et al. [9]	1993	2	Walking, running, stumbling	HIP II	Demonstrated strong relationship between activity intensity and load magnitude, with extreme peaks during perturbations	Walking 280–480% BW, running ~550% BW, stumbling up to ~870% BW	Provides upper-limit loading scenarios relevant for high-impact sports restriction	First documentation of extreme outliers
Bergmann et al. [10]	1994	1	Orthosis-assisted walking	HIP II	Shown that assistive devices can reduce hip loading, but not eliminate it	Load reduction ~30%	Supports use of load-modifying strategies in early RTP phases	Comparable effect to crutches
Bergmann et al. [11]	1995	2	Stairs vs. walking	HIP II	Found that stair negotiation increases torsional loads more than peak force magnitude	Force increase ~10–20% vs. walking	Highlights importance of torsion (not just force) in RTP decisions	Torsion relevant for loosening
Bergmann et al. [12]	1995	1	Walking, footwear	HIP II	Demonstrated that footwear alters load distribution and torsional stresses more than peak force magnitude	Forces within ~180–620% BW range	Suggests technique and gait control more important than footwear alone	Torsional component emphasized
Bergmann et al. [13]	1997	6	Load carrying	HIP II	Shown that load carriage significantly alters hip forces depending on load position (ipsilateral vs. contralateral)	Baseline ~278% BW, contralateral load increases force ~+22% per 10% BW	Relevant for sports involving asymmetrical loading (e.g., tennis, padel)	Technique-dependent modulation
McGibbon et al. [63]	1997	1	Cane gait	HIP II	Demonstrated that contralateral cane use reduces ipsilateral hip loading while redistributing forces elsewhere	Pressure-based	Supports protected RTP strategies using assistive devices	Redistribution rather than true unloading
Park et al. [67]	1999	1	Walking	HIP II	Shown that muscle co-contraction significantly contributes to joint loading beyond passive mechanics	~180–310% BW	Highlights importance of neuromuscular control in RTP	Explains discrepancy with models
Bergmann et al. [14]	2001	4	Walking, stairs	HIP II	Established standardized reference values for hip loading during common activities	Walking ~238% BW, stairs ~251–260% BW	Defines “reference envelope” used in RTP algorithms	Widely cited benchmark study
Bergmann et al. [17]	2001	5 (7 hips)	Walking/thermal study	HIP II	Demonstrated friction-induced heating during activity, suggesting that implant tribology is not captured by force magnitude alone	Demonstrated friction-induced heating during activity, suggesting that implant tribology is not captured by force magnitude alone	Indirect RTP relevance through tribological and fixation considerations	Indirect RTP relevance through tribological and fixation considerations
Heller et al. [51]	2001	4	Walking, stairs	HIP II	Demonstrated reasonable agreement between musculoskeletal models and in vivo measurements, with some variability	~12–14% difference	Supports cautious use of modelling for RTP planning	Muscle forces dominant
Heller et al. [51]	2001	4	Walking, adl	HIP II	Femoral loading dominated by axial compression with minor shear; anteversion significantly alters hip contact forces and bending moments	Increasing anteversion to 30° increases hip contact forces up to ~7% and increases bending moments, peak loads higher in stair climbing vs. walking	Suggests caution with high-demand activities (stairs, sport-like loading), implant positioning critically affects load tolerance	First integration of telemetric data with full femoral load distribution modelling, high inter-patient variability
Bergmann et al. [18]	2004	~7	Stumbling	HIP II	Identified stumbling as the highest load-generating activity measured in vivo	Peaks > 800% BW	Highlights importance of fall prevention in RTP	Extreme load scenario

Table A2. Cont.

Study	Year	Sample Size	Activity	Telemetry Implant Model	Key Finding	Numerical Outcomes (% of BW)	RTP Relevance	Notes
Stansfield et al. [70]	2003	2	Walking	HIP II	Demonstrated limitations of biomechanical models in accurately predicting in vivo forces	~2–3 × BW	Reinforces need for direct measurements in RTP guidance	Validation study
Bergmann et al. [19]	2007	Multiple datasets	Various ADLs	HIP II/III	Summarized the practical value of telemetric implants for capturing realistic in vivo loads	Not specific	Conceptually important for RTP framework and Orthoload-based interpretation	Foundational re-view/application paper rather than a single task dataset
Bergmann et al. [21]	2010	4	ADLs, stairs, stumble	HIP II	Established realistic loading spectrum including worst-case scenarios	Walking ~180–300% BW, stumbling up to ~870% BW	Defines full biomechanical envelope for RTP decision-making	ISO standards underestimate loads
Damm et al. [30]	2013	8	Walking	HIP III	First combined measurement of joint forces and friction during gait	Peak ~248% BW	Introduces multidimensional concept of load (force + friction)	High inter-individual variability
Damm et al. [31]	2013	7	Walking with crutches (2-, 3-, 4-point gait)	HIP II	Crutches reduce hip load mainly early postop	Reduced joint force by 12–17%, up to ~21% early postop	Supports assisted ambulation in early RTP phases	Load reduction diminishes after 4–6 weeks
Schwachmeyer et al. [69]	2013	6	Physiotherapy	HIP III	Demonstrated that weight-bearing exercises may exceed walking loads depending on execution	Up to ~441% BW	Critical for early rehabilitation and RTP progression	Exercise selection important
Eschweiler et al. [70]	2014	N/A	Biomechanical model comparison	N/A/in vivo comparison study	Simplified biomechanical models approximated force magnitude reasonably but were less reliable for force orientation	Comparable magnitude to in vivo data, no single %BW value	Reinforces that RTP decisions should prioritize measured telemetry where available	Highlights variability in model assumptions
Damm et al. [32]	2015	10	Walking (3–12 months postop)	HIP III	Friction decreased over time despite relatively stable contact forces, suggesting a postoperative “running-in” phenomenon	Forces stable at ~2–3 × BW, friction decreased by up to ~47%	Supports gradual progression of activity over time after THA	Important tribology-focused follow-up study
Bergmann et al. [23]	2016	10 (hip cohort)	Walking	HIP III	Demonstrated that true in vivo hip loads exceed ground reaction forces and preserve the typical double-peak gait profile	Peak ~249% BW	Confirms walking as the key benchmark activity for RTP comparisons	Useful for explaining why GRF alone is insufficient
Damm et al. [34]	2017	5	Cycling	HIP III	Showed that cycling produces lower loads than walking and is modifiable by cadence and power	Typically ≤2–2.5 × BW	Supports cycling as a safe early RTP activity	Dose-dependent loading
Damm et al. [33]	2017	10	Walking after rest	HIP III	Friction moments increase markedly at gait initiation	+32–143% average friction moment, up to 621%	Highlights risk during start-stop activities	Relevant for intermittent sports
Damm et al. [35]	2017	19	Level walking (hip vs. knee vs. spine)	HIP III	Hip loads exceed GRF significantly	Hip peak ≈249% BW, GRF ≈100–126% BW	Defines baseline RTP reference loads	Gold-standard walking benchmark
Kutzner et al. [59]	2017	12	Aquatic exercise	HIP III	Demonstrated significant load reduction in water, but with variability depending on movement velocity	32–396% BW	Supports aquatic therapy as load-modulatable RTP option	High-speed movements ↑ load
Bergmann et al. [24]	2018	9	Various activities	HIP III	Identified friction moments as critical determinants of implant stress during sustained loading	Not directly %BW	Suggests RTP should avoid prolonged static loading	Friction threshold concept
Bergmann et al. [25]	2018	N/A	Whole-body vibration	HIP III	Whole-body vibration produced hip loads well below those of walking despite variable dynamic input	Static ~93–141% BW, total load <79% of walking	Supports WBV as a low-load adjunct modality rather than a high-load RTP concern	Supports WBV as a low-load adjunct modality rather than a high-load RTP concern
Damm et al. [36]	2018	10	ADL (walking, stairs, sit-to-stand)	HIP III	Gluteal damage leads to higher joint loads	Increased fat % of gluteal muscles is correlated to increased joint forces	Muscle status critical for safe RTP	Emphasizes rehab importance

Table A2. Cont.

Study	Year	Sample Size	Activity	Telemetry Implant Model	Key Finding	Numerical Outcomes (% of BW)	RTP Relevance	Notes
Angelini et al. [3]	2018	9 (including THA subgroup)	Walking with arm-swing variations	HIP III	Arm-swing modifications changed visible kinematics but had minimal effect on hip joint loading	Walking baseline ~170% BW, no major change across variants	Suggests many gait-style modifications do not meaningfully unload the hip	Good example that kinematics ≠ kinetics
Damm et al. [38]	2019	Multiple datasets	Forward bending and lifting	HIP III	Hip forces increased progressively with trunk flexion and load, emphasizing posture-dependent loading	No single standardized %BW reported, consistent increase with forward bending	Highly relevant for gym return, lifting, and occupational RTP	Technique-dependent loading pattern
Damm et al. [39]	2021	10	Mixed ADL and activities	HIP III	Cup positioning affects friction and temperature	Temps up to ~41–43 °C, friction independent of force magnitude	Implant positioning impacts long-term RTP safety	Multimodal (in vivo + in silico)
Haffer et al. [48]	2021	6	Stretching, strengthening, aerobic	HIP III	Most exercises remained at or below walking, but selected dynamic tasks generated higher peaks	Generally around walking (~300% BW), with selective increases	Supports controlled later-phase RTP, but some drills need caution	Step-board and dynamic flexion/abduction tasks more demanding
Palmowski et al. [66]	2021	6	Nordic walking	HIP III	Found that Nordic walking produces loads comparable to normal walking	Differences ±6–9% vs. walking	Supports Nordic walking as safe RTP activity	Technique-dependent
Palmowski et al. [65]	2021	N/A	Walking with different shoe types	HIP III	Footwear modified hip loading, especially at heel strike, and also affected torsional behaviour	Increase up to ~34–47% versus barefoot at heel strike	Relevant for optimizing walking and sport re-entry mechanics after THA	Stiffer shoes increased torsional demand
Haffer et al. [49]	2022	7	Gym machines	HIP III	Demonstrated that most gym exercises produce loads ≤ walking, except single-leg variants	~128–343% BW vs. walking ~303% BW	Supports gym-based RTP with supervision	Monopod stance increases load
Bender et al. [5]	2022	16	ADLs and sports	HIP III	Showed that some supposedly “low-impact” activities may still generate substantial implant loads	Some activities exceed 4× BW	Challenges simplistic RTP classifications based only on sport label	Younger, higher-demand patients tended to generate higher loads
Alves et al. [1]	2022	8	Gait prediction study	HIP III	Ground reaction forces alone were insufficient to accurately predict true in vivo hip contact forces	No direct %BW outcome for clinical comparison	Important for future wearable/indirect monitoring, but not a substitute for telemetry	Supports benchmark role of direct measurements
Zhou et al. [61]	2023	6	Swimming	HIP III	Showed that swimming generates moderate loads, increasing with speed and technique	~157–193% BW (breaststroke), higher in crawl	Supports aquatic RTP with technique control	Velocity-dependent loading
Brandl et al. [26]	2024	14	Lifting	HIP III	Demonstrated that lifting produces high hip loads regardless of technique, with strong correlation to ergonomic risk	~294–321% BW	Highlights occupational and gym-related RTP risks	Large dataset
Bender et al. [6]	2024	14	Lifting	HIP III	Showed that lifting technique changes load direction but not magnitude	~300% BW	Suggests RTP decisions must consider torsion and load direction	Phase-dependent loading
Aschenbrenner et al. [4]	2025	5	Skiing	HIP III	Demonstrated that skiing loads are generally comparable to walking, with technique-dependent variation	~2–3× BW	Supports selected sport RTP in experienced patients	Simulator-based

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