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Functional Recovery after Revision Total Hip Arthroplasty with Acetabular Defects: The Role of Personalized Physical Therapy and Assistive Technology

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Abstract: Revision total hip arthroplasty (THA) with acetabular defects represents a major challenge in modern orthopedic practice, requiring advanced therapeutic strategies both during surgery and throughout postoperative recovery. Rehabilitation in these cases demands a personalized approach that combines conventional physical therapy with modern interactive technologies capable of enhancing neuromuscular control, functional balance, and overall quality of life. This comparative study included 40 patients who underwent revision THA with acetabular defects, divided into an experimental group (n = 20), which followed an individualized physical therapy program supplemented with exercises on the Huber 360 Platform, and a control group (n = 20), which received only conventional physical therapy. Functional assessments were performed at two time points: T0 (3 months postoperatively, before rehabilitation) and T1 (6 months postoperatively, after completing the 3-month program). The evaluation tools included the Harris Hip Score (HHS), Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), Visual Analog Scale (VAS), Timed Up and Go Test (TUG), Berg Balance Scale (BBS), Short Physical Performance Battery (SPPB), and the neuromotor analysis provided by the Huber 360 Platform. Statistical analysis revealed significant improvements in both groups, with substantially greater progress in the experimental group ($p < 0.05$ for most variables). Integrating the Huber 360 Platform into the rehabilitation protocol enhanced therapeutic efficiency by facilitating sensorimotor re-education, improving postural balance, and optimizing reaction time. Functional outcomes at T1—particularly HHS, SPPB, and BBS—were markedly superior in the experimental group. These findings support the hypothesis that technology-assisted rehabilitation provides measurable benefits in patients undergoing revision THA with acetabular defects, reinforcing the value of multimodal, feedback-driven approaches in contemporary orthopedic rehabilitation practice.

Keywords: total hip arthroplasty, acetabular revision, postoperative rehabilitation, personalized physical therapy, Huber 360 Platform, postural balance, neuromuscular control

1. Introduction

Total hip arthroplasty (THA) is recognized as one of the most effective surgical procedures for advanced osteoarthritis and other severely debilitating hip disorders. It restores mobility, alleviates pain, and significantly improves patients' quality of life [1].

Over the past decade, increasing life expectancy and higher functional demands among younger and more active individuals have led to a substantial rise in revision arthroplasties [2–5]. Revision THA remains particularly challenging in cases involving acetabular bone defects, where compromised bone stock affects implant stability and requires advanced reconstructive techniques such as bone grafting, modular components, and augmented cups [6–9].

Periprosthetic hip fractures have become an increasingly common complication in elderly and frail patients. Clinical observations show that functional performance remains reduced in over 75% of cases three months after the fracture, while more than 90% of patients experience significant loss of independence, underlining the need for early diagnosis, individualized management, and preventive rehabilitation strategies aimed at reducing long-term disability [10–12].

In this context, postoperative rehabilitation plays a crucial role in restoring functional capacity and optimizing clinical outcomes [13–17]. Personalized physical therapy facilitates joint rebalancing, muscle strengthening, recovery of range of motion, and control of balance [17–19]. The literature consistently demonstrates that well-structured rehabilitation programs reduce postoperative complications, improve gait biomechanics, and accelerate functional progress [14,20,21].

Recovery after hip arthroplasty is a complex and multidisciplinary process requiring close collaboration between orthopedic surgeons, physiotherapists, and rehabilitation specialists. The design of the rehabilitation protocol and the timing of discharge depend on multiple factors—including preoperative status, medical history, and the complexity of the surgical reconstruction—while individual progress is influenced by baseline physical condition, motivation, and personal goals [22]. These considerations emphasize the importance of personalized therapeutic planning and continuous communication within the medical team.

To enhance the effectiveness of standard rehabilitation, modern interactive technologies have begun to be incorporated into orthopedic recovery programs. The HUBER 360 system provides real-time neuromotor feedback and enables controlled, multiplanar exercises that stimulate proprioceptive and vestibular pathways [23–25]. This platform has shown promising results in improving postural balance and neuromuscular coordination across various orthopedic conditions [26,27], and early findings suggest benefits for dynamic rebalancing after joint arthroplasty [28].

A growing body of evidence supports the use of sensorimotor-feedback systems such as the HUBER 360 Evolution (LPG Systems, Valence, France) to enhance neuromuscular control, balance, and dynamic stability [29–31]. In early postoperative settings, adding HUBER 360–based balance training has been associated with superior short-term functional gains after total knee arthroplasty [28]. Randomized controlled trials in patients with chronic non-specific low back pain also reported significant improvements in trunk stability, postural control, and coordination following feedback-guided, multiplanar exercises [32,33]. A prospective intervention study is currently underway to evaluate the platform's potential to reduce fall risk in older adults [34,35]. However, no peer-reviewed studies to date have examined its application in rehabilitation after revision THA with acetabular defects.

In Romania, the use of such technologies in post-arthroplasty rehabilitation remains limited. Therefore, the aim of this study is to comparatively evaluate the effectiveness of a personalized physical therapy program assisted by the HUBER 360 system versus a conventional rehabilitation program in patients who underwent revision THA with acetabular defects, in order to provide objective data that may contribute to optimizing national rehabilitation protocols.

Revision THA in the presence of Paprosky type II–III acetabular defects leads to significant biomechanical and neuromuscular modifications, such as altered hip center of rotation, muscle imbalance, and impaired proprioception due to capsuloligamentous changes and repeated surgical procedures. These alterations negatively affect postural control and the efficiency of automatic movement strategies, reinforcing the need for a sensorimotor reeducation approach. Training with the HUBER 360 platform facilitates proprioceptive recalibration, enhances neuromuscular coordination, and supports the integration of visual, vestibular, and somatosensory inputs, promoting adaptation to the revised hip's altered biomechanics.

Although existing literature highlights the advantages of early postoperative rehabilitation and the role of sensorimotor feedback in balance re-education, few studies have investigated these methods in the context of acetabular revision. The present study addresses this gap by comparing a conventional physical therapy protocol with one augmented by the HUBER 360 system in patients with Paprosky type II–III acetabular defects. Our objective is to determine whether integrating this technology accelerates and enhances functional recovery, thereby supporting the modernization of orthopedic rehabilitation strategies.

2. Materials and Methods

2.1. Patient cohort

The study was conducted at the Central Military Emergency University Hospital "Dr. Carol Davila" (Bucharest, Romania), within the Departments of Orthopedics and Traumatology and Physical Medicine and Rehabilitation II.

A total of 40 patients who underwent revision total hip arthroplasty (THA) for Paprosky type II–III acetabular defects were included.

They were retrospectively assigned to two groups:

- Experimental group (n = 20): individualized physical therapy + HUBER 360 Evolution training
- Control group (n = 20): individualized standard physical therapy only

2.2. Inclusion and Exclusion Criteria

Inclusion criteria

- age 55–82 years;
- unilateral acetabular revision THA;
- Paprosky type II–III acetabular defects;
- ability to follow a 3-month rehabilitation program;
- written informed consent.

Exclusion criteria

- severe neurologic conditions (stroke, Parkinson's disease);
- severe cognitive/psychiatric impairment;
- major musculoskeletal limitations (amputation, recent fracture);
- cardiac or respiratory instability;
- refusal or inability to consent.

2.3. Study design

Rehabilitation began at 3 months postoperatively (T0) and continued for 3 months, ending at T1 (6 months postoperatively).

Both groups followed an individualized physical therapy program 3 times/week, 60 minutes/session.

The experimental group completed the same protocol + two additional weekly HUBER 360 sessions (20–30 minutes/session).

Standardization of therapist involvement

A single licensed physical therapist delivered all rehabilitation sessions and functional assessments for both groups, ensuring consistent implementation and eliminating inter-therapist variability.

2.3.1. Detailed Training Parameters on the HUBER 360 Platform

Platform characteristics and purpose

The HUBER 360 Evolution (LPG Systems, France) is a multi-axis motorized platform equipped with force sensors and interactive handles, designed to train postural stability, neuromuscular coordination, and reaction time under controlled instability.

General training structure

Sessions were delivered in Assessment & Progressive Training Mode and included:

- controlled anteroposterior (AP) and mediolateral (ML) tilts
- combined AP+ML movements (elliptical paths)
- progressive increases in tilt amplitude (2–4° initially → 6–8°)
- incremental oscillation speeds (level 1–2 → level 4–5)
- adaptive handle resistance controlled by force sensors
- real-time visual feedback (CoP trajectory, symmetry index, movement targets).

Progressive training phases

Weeks 1–2: Basic stabilization

- low amplitudes (2–3°)
- minimal oscillation speed
- static control exercises
- minimal handle resistance
- emphasis on symmetry and trunk alignment

Weeks 3–6: Proprioceptive and postural reactivity training

- amplitudes 4–6°
- introduction of multiplanar instability
- directional loading tasks
- moderate adaptive resistance
- visual-guided tracking tasks

Weeks 7–12: Dynamic neuromuscular control

- amplitudes 6–8°
- higher oscillation speeds (levels 4–5)
- dual-task postural training
- global strength tasks with increased resistance
- maintenance of CoG in target zones under instability

Types of exercises used

- Static balance: stance on unstable surface, symmetry control, trunk stabilization
- Dynamic balance: weight shifting in 4/8 directions, rapid corrective actions
- Coordination tasks: target tracking, directional path-following
- Multiplanar stabilization: pelvic control under AP+ML movement
- Strength integration: interactive handle resistance engaging trunk and pelvic muscles

Therapist involvement

Although the platform provides automated progression, the physiotherapist ensured:

- pelvic and trunk alignment
- avoidance of compensatory movements
- control of exercise quality
- fatigue and pain monitoring
- real-time adjustment of amplitude/resistance if tasks became too difficult

Clinical correlation with outcomes

The progressive neuromuscular loading provided by the HUBER 360 directly reflects the functional improvements observed at T1 in balance (BBS), mobility (TUG), strength (SPPB), and hip range of motion.

2.4. Rehabilitation Protocol

Both groups followed an identical 60-minute physiotherapy protocol (3 sessions/week for 12 weeks), based on:

- individualized exercise selection
- progressive loading
- functional specificity (gait, balance, periarticular strength)

- joint protection tailored to Paprosky II–III defects

Control group protocol (conventional physical therapy) included:

- joint mobilization (hip, knee, ankle)
- self-stretching of shortened muscles
- strengthening (isometrics, elastic bands, sit-to-stand, step-ups)
- gait retraining (stride correction, stance control, pelvic alignment)
- balance training (supportive stance, weight transfers)
- manual progression by the physiotherapist

Experimental group protocol (conventional + HUBER 360) included all conventional exercises plus two weekly HUBER sessions with:

- proprioceptive training under controlled instability
- CoP tracking and symmetry feedback
- multiplanar stabilization tasks
- adaptive resistance and interactive motor tasks
- objective automatic progress reports

2.5. Functional assessment instruments

Functional assessments were conducted by a multidisciplinary team of orthopedic surgeons and physical therapists at two time points:

- T0: three months postoperatively, prior to rehabilitation initiation;
- T1: six months postoperatively, after completing the three-month program.

The following validated instruments were used:

Harris Hip Score (HHS)

The HHS assesses hip function by combining patient-reported pain and daily activity limitations with clinician-evaluated gait, range of motion, and functional capacity [36,37]. Total scores range from 0–100, with higher values reflecting better hip function. Conventional interpretations classify scores <70 as poor, 70–80 as fair, 80–90 as good, and 90–100 as excellent.

Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)

The WOMAC evaluates pain (0–20), stiffness (0–8), and physical function (0–68), using a 0–4 Likert scale for each item. Higher scores indicate more severe symptoms and poorer joint function [38–40].

Visual Analog Scale (VAS)

Pain intensity was measured using a 10-cm VAS, where 0 indicates "no pain" and 10 "worst imaginable pain." Patients marked their current pain level on the horizontal line [41–43]. The VAS is a highly sensitive measure with excellent test–retest reliability (ICC ≈ 0.99) and strong responsiveness in musculoskeletal and postoperative pain assessment [44–47].

Timed Up and Go Test (TUG)

The TUG quantifies functional mobility and fall risk by measuring the time required to stand up from a chair, walk 3 meters, turn, return, and sit down. Shorter times indicate better mobility and balance. It is widely used in orthopedic and geriatric rehabilitation to monitor functional progress and detect mobility limitations [48,49].

Berg Balance Scale (BBS)

The BBS consists of 14 tasks evaluating static and dynamic balance, each scored from 0 to 4, for a maximum of 56 points. Higher scores reflect better postural control and lower fall risk. The scale is extensively validated and considered a gold standard in balance evaluation across orthopedic and neurological populations [50–52].

Short Physical Performance Battery (SPPB)

The SPPB integrates balance testing, gait speed, and chair-rise performance into a composite score ranging from 0 (severe impairment) to 12 (optimal lower-limb function). It is widely used in clinical and research settings as a predictor of mobility decline and rehabilitation potential [53,54].

HUBER 360 Evolution Platform Assessment

In the experimental group, the HUBER 360 Evolution platform provided objective measurements of postural stability, neuromuscular coordination, center-of-pressure control, and reaction time. The system integrates multi-axis platform motion and handle-based force sensors, allowing quantification of balance fluctuations and neuromotor responses under controlled instability. Previous studies have reported improvements in postural coordination and pain reduction in programs incorporating HUBER-based neuromotor training [32,33].

Goniometry

Hip range of motion (flexion, extension, abduction, adduction) was measured using a universal goniometer following standardized alignment protocols. Measurements were taken consistently at both time points to ensure reproducibility and objective tracking of mobility evolution.

6-Minute Walk Test (6MWT)

The 6MWT assessed submaximal exercise capacity by measuring the distance walked in six minutes on a flat, unobstructed corridor. It provides an estimate of functional endurance and cardiopulmonary efficiency and is widely used to monitor postoperative recovery and adaptation to physical therapy intensity [55–57]. Symptoms encountered during the test (e.g., fatigue, dyspnea, pain) were documented to identify exercise limitations [58].

All instruments were administered according to standardized methodological guidelines.

2.5. Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics version 27 (IBM Corp., Armonk, NY, USA) and Python 3.10. Numerical computations were conducted with NumPy 1.23, data organization with pandas 1.5, inferential tests with SciPy 1.9, and graphical visualization with Matplotlib 3.6.

Normality of continuous variables was verified using the Kolmogorov–Smirnov test.

- For normally distributed variables, paired-samples t-tests assessed within-group changes (T0–T1), and independent-samples t-tests compared groups at T1.
- For non-normally distributed variables, Mann–Whitney U tests were used.
- Categorical variables were analyzed using chi-square (χ^2) tests.

The significance threshold was set at $p < 0.05$. Effect sizes were calculated for all primary outcomes. For parametric tests, effect size was expressed as Cohen's d, interpreted according to established thresholds: small (0.2), medium (0.5), and large (≥0.8) [59–61]. For non-parametric comparisons, effect size was calculated as the r-coefficient derived from test statistics.

Because several variables showed baseline differences between groups, the primary analysis focused on the absolute change ($\Delta = T1 - T0$), accompanied by effect size calculations, thereby minimizing baseline imbalance and improving the accuracy of between-group comparisons.

Descriptive statistics (mean, standard deviation, and 95% confidence intervals) were reported for all continuous variables. Internal validity was supported by complete follow-up and consistent scoring across evaluators.

3. Results

3.1. Demographic characteristics

No statistically significant differences were found between the two groups regarding baseline demographic characteristics (age, sex, or type of reconstruction), confirming the homogeneity of the sample.

The mean age was 63.1 ± 6.3 years in the experimental group and 62.9 ± 5.8 years in the control group ($p = 0.74$), as shown in Table 1.

Table 1. Baseline demographic characteristics of the study groups.

Characteristics	Experimental (n = 20)	Control (n = 20)	p-value
Age (mean ± SD)	63.1 ± 6.3 years	62.9 ± 5.8 years	0.74
Sex (F/M)	7 / 13	10 / 10	0.65

Although the groups were demographically similar, significant differences were identified in several functional parameters at T0.

The experimental group showed higher baseline values for HHS, SPPB, Tinetti, and greater hip extension and abduction (p ranging from 0.0008 to 0.0127).

Conversely, WOMAC, VAS, BBS, and MMT scores showed no significant baseline differences.

3.2. Evolution of functional scores between T0 and T1

All patients were evaluated at T0 (3 months postoperatively) and T1 (6 months postoperatively). Both groups showed statistically significant improvements ($p < 0.05$), with consistently greater progress in the experimental group. Below are the results for each instrument.

1. Harris Hip Score (HHS)

The Harris Hip Score (HHS) showed significant functional improvement in both groups.

In the experimental group, the mean HHS increased from 48.75 (95% CI: 46.47–51.03) at T0 to 70.55 (95% CI: 67.61–73.49) at T1, with non-overlapping confidence intervals, indicating a statistically significant gain.

In the control group, the mean rose from 42.45 (95% CI: 40.38–44.52) to 62.70 (95% CI: 60.46–64.94), also confirming a significant within-group improvement.

At baseline (T0), the experimental group scored higher (48.75 vs. 42.45), with the Mann–Whitney test yielding $p < 0.001$.

At T1, the experimental group reached 70.55 compared with 62.70 in the control group ($p < 0.001$), demonstrating superior recovery of hip function (see Figure 1A).

2. WOMAC (Western Ontario and McMaster Universities Osteoarthritis Index)

The WOMAC index showed consistent improvement in both groups.

In the experimental group, the mean score decreased from 68.3 (95% CI: 65.14–71.46) at T0 to 47.9 (95% CI: 44.18–51.62) at T1.

In the control group, the mean declined from 67.1 (95% CI: 63.18–71.02) to 54.6 (95% CI: 50.38–58.82).

At baseline (T0), no significant difference was found between groups ($p = 0.620$).

At T1, the experimental group showed a significantly lower (better) mean score (47.9 vs. 54.6; $p = 0.017$).

The change (Δ) was −20.4 in the experimental group compared with −12.5 in the control group ($p < 0.001$), confirming superior symptom reduction (see Figure 1B).

3. Visual Analog Scale (VAS)

VAS scores improved markedly in both groups.

In the experimental group, the mean score decreased from 7.2 (95% CI: 6.64–7.76) at T0 to 3.85 (95% CI: 3.18–4.52) at T1.

In the control group, pain intensity decreased from 7.85 (95% CI: 7.34–8.36) to 5.95 (95% CI: 5.51–6.39).

Baseline differences were nonsignificant ($p = 0.075$).

At T1, pain levels were significantly lower in the experimental group (3.85 vs. 5.95; $p < 0.001$).

The mean change (Δ) was −3.35 in the experimental group and −1.9 in the control group ($p < 0.001$), indicating enhanced postoperative analgesic benefit when technology-assisted therapy was included (see Figure 1C).

4. Timed Up and Go Test (TUG)

TUG times decreased significantly in both groups.

In the experimental group, the mean completion time decreased from 19.15 s (95% CI: 18.61–19.69) at T0 to 14.64 s (95% CI: 13.78–15.50) at T1, with non-overlapping confidence intervals, indicating a significant enhancement in functional mobility.

In the control group, the mean TUG time decreased from 20.67 s (95% CI: 20.01–21.32) to 17.22 s (95% CI: 16.53–17.91), also showing a significant postoperative improvement.

Both groups showed significant mobility gains, but the improvements were more pronounced in the experimental group, supporting the added value of proprioceptive and dynamic balance training (see Figure 1D).

5. Berg Balance Scale (BBS)

BBS scores increased substantially in both groups.

In the experimental group, the mean score increased from 34.45 (95% CI: 32.72–36.18) at T0 to 45.55 (95% CI: 43.30–47.80) at T1.

The control group improved from 31.9 (95% CI: 30.48–33.32) to 43.2 (95% CI: 41.66–44.74).

The magnitude of improvement was greater in the experimental group, reflecting superior recovery of both static and dynamic balance capabilities (see Figure 1E).

6. Short Physical Performance Battery (SPPB)

SPPB scores improved significantly over time.

The experimental group progressed from 4.95 to 7.85, while the control group improved from 3.95 to 6.9.

Baseline differences favored the experimental group ($p = 0.0022$).

At T1, performance remained significantly better ($p = 0.0052$), confirming enhanced global physical performance in the technology-assisted cohort (see Figure 1F).

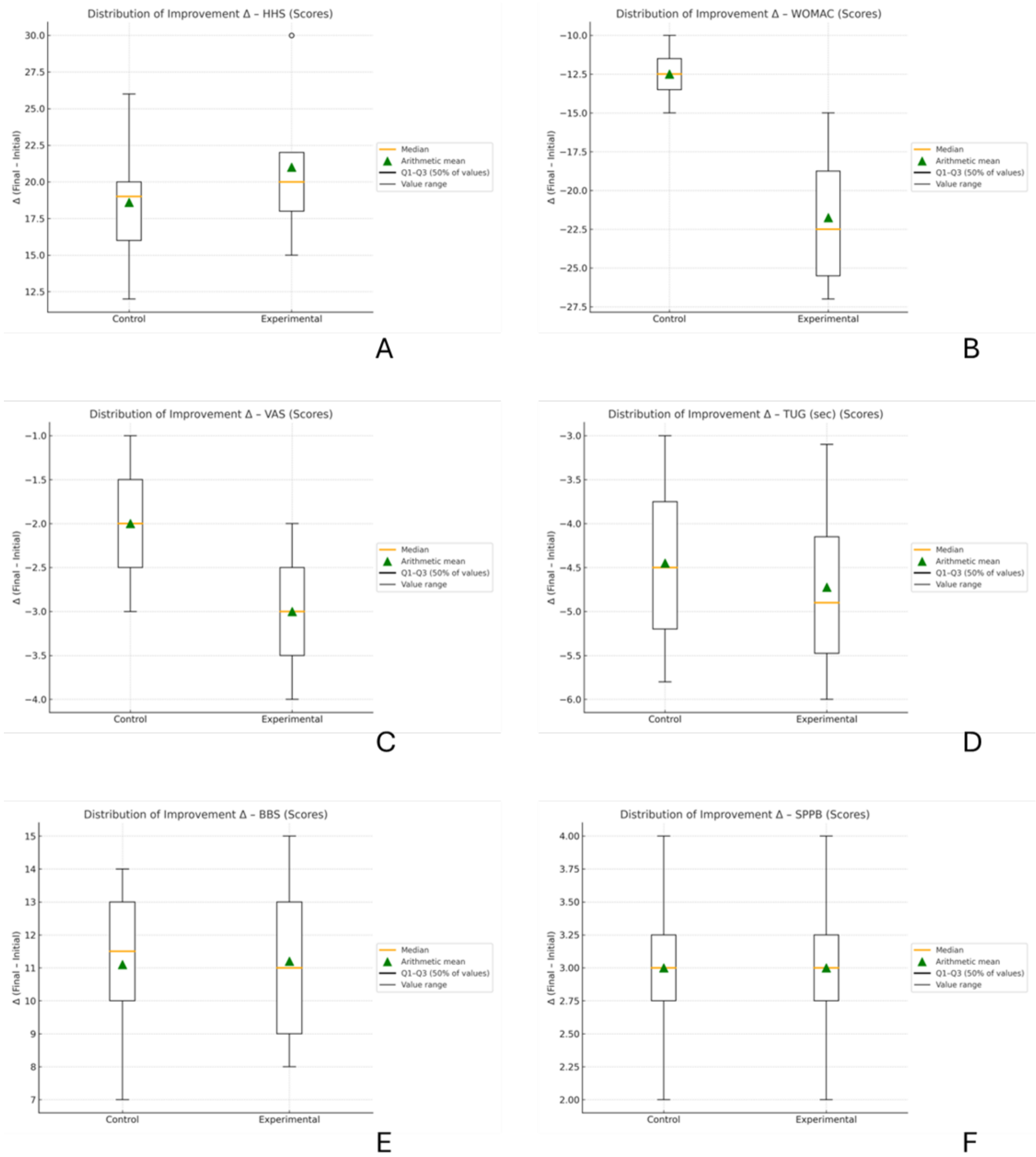

Figure 1. Distribution of improvement (Δ) for the main functional outcomes between T0 and T1: (A) HHS; (B) WOMAC; (C) VAS; (D) TUG; (E) BBS; (F) SPPB.
Each boxplot displays median values, arithmetic means, interquartile ranges, and full value dispersion for both groups.

7. Huber 360 Platform (experimental group only)

The Huber 360 Platform, used exclusively in the experimental group, evaluates postural stability, balance, reaction time, and neuromuscular control through multidirectional stimuli and real-time feedback.

Significant improvements were observed across all parameters: +38% in static balance, +41% in neuromuscular control, and a reduction in reaction time from 1.9 s to 1.2 s ($p < 0.001$).

These results highlight the contribution of technology-assisted proprioceptive training to balance optimization and motor control enhancement during postoperative rehabilitation.

8. Goniometry for range of motion

Hip joint range of motion improved significantly in both groups, with superior gains in the experimental cohort. Goniometric evaluation confirmed progressive restoration of joint mobility across all assessed planes.

In the experimental group, flexion increased from 72.5° (95% CI: 68.64–76.36) at T0 to 89.75° (95% CI: 85.49–94.01) at T1, extension from 2.25° (95% CI: 1.73–2.77) to 9.65° (95% CI: 8.64–10.66), and abduction from 19.4° (95% CI: 18.13–20.67) to 30.55° (95% CI: 28.80–32.30). All changes showed non-overlapping confidence intervals and $p < 0.001$, confirming highly significant improvements.

In the control group, improvements were also observed but less pronounced: flexion increased from 67.6° (95% CI: 63.77–71.43) to 80.1° (95% CI: 75.85–84.35), extension from 1.05° (95% CI: 0.66–1.44) to 7.2° (95% CI: 6.49–7.91), and abduction from 16.5° (95% CI: 14.90–18.10) to 22.9° (95% CI: 21.24–24.56), all with $p < 0.01$.

Between-group comparisons at T1 confirmed the superior recovery of the experimental cohort: flexion ($p = 0.0018$), extension ($p = 0.0006$), and abduction ($p < 0.001$). The greater amplitude gains (Δ) in the experimental group support the added value of sensorimotor-feedback training in restoring complex hip kinematics and reducing compensatory movement patterns.

Flexion, extension, and abduction improvement distributions are illustrated in Figure 2A–C.

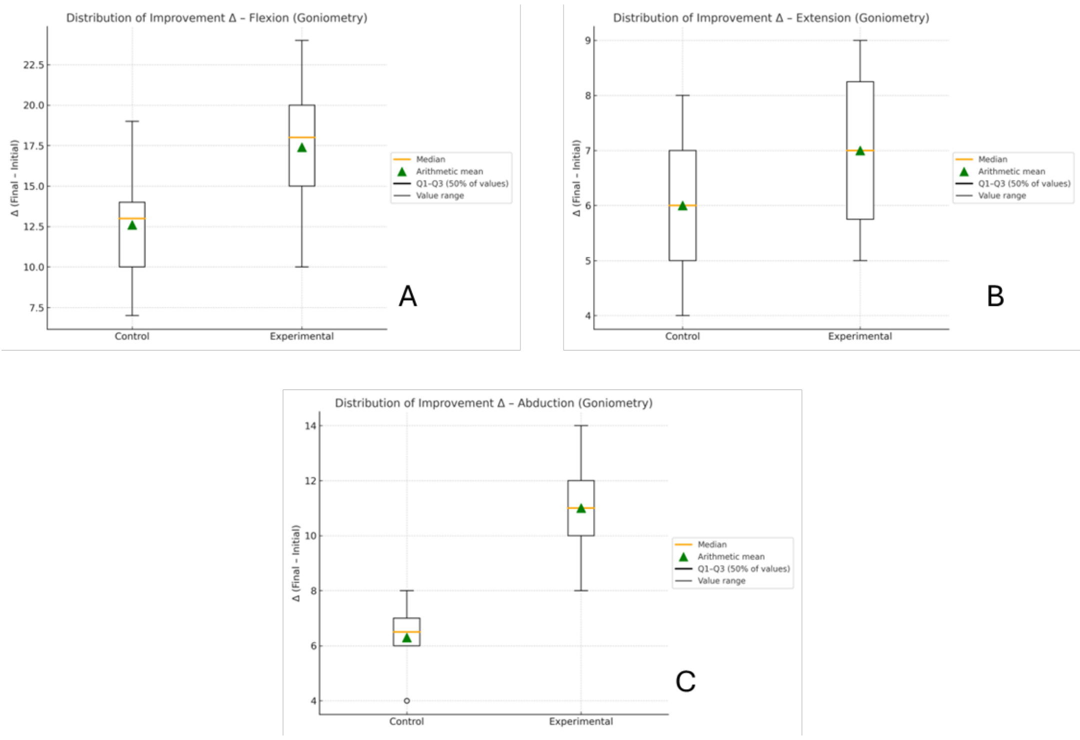

Figure 2. Distribution of improvement (Δ) in hip range of motion between T0 and T1: (A) Flexion; (B) Extension; (C) Abduction.
Each boxplot shows the median, arithmetic mean, interquartile range, and total value dispersion for both groups.

9. Six-Minute Walk Test (6MWT)

The 6-Minute Walk Test (6MWT), a validated indicator of submaximal exercise capacity, showed significant improvement in both groups.

In the experimental group, walking distance increased from 241 m at T0 to 375 m at T1 (Δ = +134 m, $p < 0.001$), indicating enhanced endurance, better cardiopulmonary efficiency, and improved adaptation to sustained physical effort.

In the control group, distance increased from 238 m to 310 m (Δ = +72 m, $p < 0.001$), confirming a beneficial effect of conventional rehabilitation, though less pronounced.

The significantly greater functional gain observed in the experimental group demonstrates the advantage of technology-assisted physical therapy in improving exercise tolerance and overall mobility during postoperative recovery after acetabular revision.

4. Discussion

The results of this study confirm the initial hypothesis that integrating Huber 360–assisted exercises into postoperative rehabilitation significantly enhances functional outcomes in patients undergoing revision total hip arthroplasty with acetabular defects. Although both groups demonstrated statistically significant improvements across all assessment instruments, the experimental group showed consistently superior gains at T1, underscoring the added therapeutic value of sensorimotor training, neuromuscular re-education, and real-time feedback.

Functional scores and joint stability

The Harris Hip Score (HHS) and WOMAC index showed greater improvement in the experimental group, supporting the premise that proprioceptive and dynamic balance exercises contribute to enhanced joint stabilization. The substantial increase in HHS scores exceeded the established minimum clinically important difference (MCID of 7–10 points), aligning with evidence that structured postoperative rehabilitation contributes meaningfully to functional restoration after total hip arthroplasty [62].

Similarly, WOMAC outcomes improved more prominently in the experimental group. Bellamy et al. (1988) originally validated WOMAC as a sensitive tool for assessing recovery after joint replacement [63], and subsequent studies—such as those by Quintana et al. (2005) and Halket et al. (2008)—demonstrated consistent postoperative improvements, tightly correlated with pain reduction and functional recovery [64,65]. The present results mirror these findings, indicating that personalized, feedback-driven rehabilitation enhances both objective and patient-reported outcomes.

Analysis of MCID thresholds further reinforces the clinical relevance of these improvements. Both groups exceeded MCID benchmarks for HHS, WOMAC, and TUG, but the magnitude of change was consistently higher in the experimental cohort, highlighting the effectiveness of Huber 360–assisted interventions.

Pain reduction and dynamic mobility

The marked reduction in VAS scores in the experimental group demonstrates the analgesic benefits of integrated proprioceptive and motor training. According to Bijur et al. (2003), an improvement of ≥1.3 points is clinically significant [46]; the 3.35-point reduction observed here confirms a robust therapeutic effect. Beyond biomechanical improvements, these findings may reflect central modulation of nociceptive pathways, as neurophysiological studies indicate that proprioceptive stimulation enhances cortical integration and reduces pain perception in musculoskeletal disorders [66,67].

The Timed Up and Go (TUG) results further support the positive impact of dynamic neuromotor training. The reduction of 5 seconds in the experimental group surpasses the widely cited clinical threshold of 3 seconds [68]. Similar improvements have been reported in studies evaluating proprioceptive and neuromotor retraining after lower-limb arthroplasty [69,70]. Enhanced TUG performance in our cohort likely reflects gains in lower-limb strength and anticipatory postural adjustments—key components of safe functional mobility.

Balance, postural control, and overall performance

Both BBS and SPPB scores improved markedly, with superior results in the experimental group, confirming the impact of multisensory training delivered by the Huber 360 system. The platform’s controlled instability, biofeedback, and progressive load modulation stimulate efficient motor adaptation.

Targeted balance exercises have long been recognized as an effective strategy for reducing fall risk [71], the beneficial influence of proprioceptive training on BBS performance being well documented in the literature [72]. The 11-point increase observed in our study represents a clinically meaningful transition from moderate to good balance proficiency.

Similarly, the SPPB improvement exceeded the MCID of 1 point, confirming the recovery of lower-limb function, gait quality, and physical performance [73,74]. These results suggest that Huber 360–based training successfully enhances the neuromuscular coordination required for safe ambulation and daily activities.

Joint range of motion and functional recovery

The goniometric analysis revealed clear improvements in all measured hip joint movements—flexion, extension, and abduction—across both groups, with superior gains in the experimental one. The lack of overlap in 95% confidence intervals and statistically significant differences in flexion and abduction at T1 underscore the added value of progressive, feedback-based training. The improvement of 16° in flexion and 11° in abduction observed in the experimental group can be attributed to enhanced muscle elasticity, better joint proprioception, and increased activation of stabilizing muscles. These findings are consistent with previous research emphasizing the importance of dynamic stretching and assisted movement training for optimizing range of motion and functional reintegration after arthroplasty.

Endurance and cardiopulmonary efficiency

The 6-Minute Walk Test (6MWT) results indicate substantial improvement in submaximal exercise capacity, with an average increase of 134 meters in the experimental group compared with 72 meters in the control group. This aligns with findings from Kennedy et al. (2005), who reported that the 6MWT is a sensitive indicator of postoperative functional recovery after hip and knee arthroplasty [75]. Similarly, Enright and Sherrill (1998) established its value as a reliable measure of aerobic capacity and endurance in clinical rehabilitation settings [76]. The increase in walking distance reflects improved cardiovascular endurance and muscular efficiency, essential parameters for regaining independence in activities of daily living. Enhanced 6MWT performance also suggests better coordination between the lower-limb kinetic chain and trunk stabilization, often neglected in standard rehabilitation protocols but directly targeted through the Huber 360 system.

Clinical relevance and technological implications

Collectively, these results underscore the multifactorial benefits of integrating the Huber 360 Platform into orthopedic rehabilitation. The combination of proprioceptive stimulation, dynamic postural control, and real-time biofeedback supports faster and more complete recovery of functional capacities. The device enables individualized load modulation, allowing therapists to tailor the program according to each patient's neuromuscular profile and progression pace. This personalized approach aligns with current trends in precision rehabilitation, emphasizing adaptability, motivation, and continuous monitoring of outcomes.

The findings also align with emerging literature supporting technology-assisted rehabilitation. For example, a pilot study of the HUBER 360 Evolution platform demonstrated significant improvements in trunk flexibility, pain, and muscle endurance after six weeks of targeted training in patients with non-specific chronic low back pain [32]. Although data are still limited in orthopedic populations, these results support the argument that integrating sensor-based balance and neuromuscular training platforms into standard rehabilitation may offer beneficial adjuncts to conventional physiotherapy programs.

Limitations, Strengths, and Future Direction

Despite the promising results, this study presents certain limitations. The sample size was relatively small, which may limit the generalizability of the findings. The follow-up period of only six months precludes conclusions regarding the long-term maintenance of functional gains. Furthermore, the absence of objective biomechanical assessments—such as three-dimensional gait analysis, surface electromyography, or force plate data—restricts a deeper understanding of the underlying motor control adaptations. Minor variations in the execution of the exercise protocol between therapists could also have influenced outcomes.

A key limitation of this study is the lack of long-term follow-up after the completion of the rehabilitation program. The results presented reflect patient progress up to six months postoperatively, during which consistent functional improvements were observed, including significant increases in HHS and SPPB scores, reductions in WOMAC and VAS scores, and enhanced mobility (TUG, 5xSTS) and balance (BBS, Tinetti). However, it remains unclear whether these improvements are maintained, stabilized, or diminished at extended time points (e.g., 12 or 24 months), when tissue remodeling, neuromuscular adaptation, and potential late complications may affect functional performance.

The absence of long-term monitoring limits the ability to assess the durability of the personalized intervention and the actual impact of the HUBER 360 platform on extended recovery. Given the well-documented variability in revision arthroplasty recovery, future studies should incorporate longitudinal tracking to determine whether the six-month benefits are sustained, amplified, or attenuated over time.

Future research should include larger, multicentric samples and extended follow-up periods (12–24 months) to validate the sustainability of observed effects. The integration of advanced quantitative assessments, including motion capture, wearable sensors, and electromyographic feedback, would provide more detailed insight into biomechanical and neuromuscular mechanisms. Comparative studies evaluating combinations of technologies—such as virtual reality, vibratory feedback, or robotic-assisted devices—could further refine and personalize postoperative rehabilitation strategies.

Among the strengths of the present study are the uniform application of the rehabilitation protocol by a multidisciplinary team and the absence of loss to follow-up, ensuring high internal validity. The methodological rigor and use of multiple complementary assessment tools—functional, subjective, and objective—offer a comprehensive perspective on recovery dynamics after revision hip arthroplasty.

No a priori sample size calculation was performed in this study, as the enrolled cohort reflected the total number of consecutive eligible patients treated during the study period, according to predefined inclusion criteria. Thus, the total sample size (N = 40; 20 in the experimental group and 20 in the control group) realistically represented the clinical availability of revision total hip arthroplasty cases with Paprosky type II–III defects, eligible for six-month follow-up. Although a prospective power analysis was not conducted, post hoc statistical power calculations based on observed effect sizes indicate that the sample was sufficient for detecting several meaningful outcomes.

The lack of an a priori power calculation constitutes a methodological limitation, as it prevents estimating the necessary sample size for detecting small but clinically relevant differences between groups. Nevertheless, the inclusion of all eligible patients and complete follow-up enhances the clinical relevance of the findings and supports the generation of hypotheses for future studies.

Patient allocation was not randomized, which may introduce selection bias. The experimental group had better baseline functional scores (HHS, SPPB, Tinetti) and greater hip extension and abduction ROM at T0, suggesting that patients with higher initial functional status were preferentially included in the HUBER 360-assisted program. Although change scores (Δ) were analyzed and effect sizes calculated to mitigate the influence of these baseline differences, the potential impact of unmeasured confounding variables on the final results cannot be entirely excluded.

Overall, the results confirm that integrating modern technological platforms such as the Huber 360 enhances the effectiveness of standard rehabilitation programs. By promoting faster pain reduction, improved balance, and greater functional autonomy, this approach supports the paradigm shift toward personalized, feedback-driven rehabilitation in orthopedic recovery.

The generalizability of the results must be interpreted in light of specific design constraints. The cohort originated from a single center, reflecting local protocols and expertise, and rehabilitation was conducted by a single therapist, ensuring consistency but limiting transferability to settings with diverse teams. Furthermore, only Paprosky type II–III defects were included, which restricts applicability to cases with minor defects or highly complex reconstructions. Differential access to HUBER 360 technology may pose another barrier to replication. However, for orthopedic centers frequently managing moderate-complexity acetabular revisions and implementing similar sensorimotor interventions, the findings of this study offer robust and clinically relevant insights.

5. Conclusions

The results of this study demonstrate the major importance of integrating modern technologies, such as the Huber 360 Platform, into postoperative rehabilitation protocols for patients undergoing revision total hip arthroplasty with acetabular defects. The significant improvements observed in functional, balance, pain, and mobility scores indicate faster and more efficient recovery in the experimental group compared with the control group, emphasizing the added value of technology-assisted therapy. Personalized physical therapy programs combined with sensorimotor-assisted exercises represent a superior strategy to conventional approaches, enhancing functional reintegration and postoperative independence.

Through its ability to provide real-time neuromuscular and proprioceptive feedback, the Huber 360 Platform emerges as a valuable tool for improving joint stability and postural control, thereby contributing to the prevention of relapse, complications, and postoperative functional imbalance.

Beyond the immediate benefits, this study highlights the need to broaden research in this field. Future investigations should include larger and more diverse—preferably multicentric—samples to validate the generalizability of the results. It would also be pertinent to integrate advanced biomechanical assessment methods, such as motion capture systems, surface electromyography (sEMG), and gait analysis platforms, to gain deeper insight into the functional mechanisms underlying recovery.

Long-term follow-up evaluations at 12 and 24 months would be valuable to assess the sustainability of the functional gains achieved. Additionally, exploring differential treatment responses according to the severity of acetabular defects could support a more rigorous personalization of therapeutic protocols.

In the future, the development of national and international clinical guidelines incorporating such technologies into standard rehabilitation practice could optimize not only functional outcomes but also treatment costs and duration. At the same time, further research should explore the psychological impact of technology-assisted recovery, post-intervention quality of life, patient satisfaction, and engagement—dimensions increasingly recognized as integral to patient-centered rehabilitation.

Overall, this study provides evidence supporting the effectiveness of technology-enhanced rehabilitation in patients with revised hip arthroplasty and outlines new directions for the evolution of orthopedic rehabilitation—toward personalization, interdisciplinarity, and sustained clinical efficiency.

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