Effects of Exercise Intensity on Musculoskeletal Injury Healing and Functional Recovery in College Students

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ABSTRACT This randomized controlled trial examines how exercise intensity affects musculoskeletal injury healing and functional recovery in college students. A total of 140 undergraduates with confirmed Grade I or II musculoskeletal injuries were randomly assigned to low-intensity exercise, moderate-intensity exercise, high-intensity exercise, or conventional physical therapy. All participants completed a 12-week intervention, with outcomes assessed through biological markers of healing, objective functional performance, pain perception, and health-related quality of life. The results show that moderate-intensity exercise at 55%–70% HRmax produced the most favorable outcomes across inflammatory markers, isokinetic peak torque, joint range of motion, dynamic balance, VAS pain ratings, and SF-36 subscales. Highintensity loading was associated with inflammatory rebound and higher re-injury risk during early recovery, while conventional therapy produced the weakest overall improvement. The findings provide evidence-based guidance for campus rehabilitation programs and support future integration of biomedical sensing and signal analysis into individualized exercise monitoring.

INDEX TERMS exercise intensity,musculoskeletal injury,functional recovery,biomedical sensing,signal analysis

I. INTRODUCTION

MUSCULOSKELETAL injuries shows that public health concerns among college students are significant. Moreover, the continued expansion of physical education curricula indicates that rising rates of student sport participation have contributed to this trend. Furthermore, the significant findings demonstrate that such injuries disrupt not only physical health but also academic functioning. Given that skeletal muscle represents a core component of the human movement system, the evidence shows that its repair involves complex metabolic regulation and cell signaling networks. Injury repair shows metabolic changes affect tissue regeneration. However, the key results indicates that physical activity activates multiple signaling pathways that support tissue repair. Additionally, the significant evidence shows that these pathways include the regulation of satellite cell proliferation, extracellular matrix remodeling, and angiogenesis. Therefore, the important findings demonstrate that these mechanisms could provide a theoretical basis for exercise-based rehabilitation interventions [2]. Nevertheless, the results indicates that healing is not simply a matter of cellular repair. Mechanisms show immune regulation shapes recovery. In light of the evidence, the findings shows that innate and adaptive immune cells work in coordination across the successive stages of skeletal muscle regeneration. Thus, the significant results indicates that their interactions largely determine both the speed and quality of tissue restoration [3]. Moreover, the key evidence demonstrates that post-injury inflammation appears to be a critical initiating event in the healing cascade. Inflammation shows intensity shapes proliferation phases. However, the findings shows that excessive or prolonged inflammatory activity could substantially impede functional recovery [4]. Furthermore, the significant evidence indicates that moderate inflammatory signaling facilitates the clearance of necrotic tissue and the recruitment of repair cells. Given that the results demonstrate that maintaining an appropriate inflammatory balance appears essential, the important findings shows that this represents a central mechanism underlying full structural and functional recovery of skeletal muscle [5]. Therefore, the key evidence indicates that the polarization states of distinct macrophage subpopulations play a significant regulatory role in the transition from injury response to exercise-induced hypertrophy. Macrophage states link injury response to hypertrophy. Notwithstanding the complexity of these mechanisms, the findings shows that a deeper understanding could inform more targeted rehabilitation strategies [6]. Moreover, the significant results indicates that systematic reviews and meta-analyses demon-

strate that higher-intensity exercise interventions appear to outperform low-intensity approaches in reducing chronic musculoskeletal pain. Additionally, the important evidence shows that exercise intensity selection appears to be a decisive variable in rehabilitation outcomes [7]. Evidence shows intensity gaps persist in college populations. However, the findings indicate that rigorous studies examining how different exercise intensities affect musculoskeletal healing in college student populations remain scarce. In light of the results, the significant evidence shows that existing rehabilitation protocols lack sufficient evidence tailored to the physiological characteristics of this group. Thus, the present study demonstrates that systematically investigating how varying exercise intensities influence musculoskeletal injury healing and functional recovery could provide a theoretically grounded framework. Study shows intensity intervention addresses molecular mechanisms and functional recovery.

II. LITERATURE REVIEW

Research on exercise intervention and musculoskeletal injury rehabilitation shows that the field has grown considerably in recent years. However, the standardization of exercise prescription dosage indicates that an unresolved problem remains central to the evidence base. Furthermore, methodological appraisals of systematic reviews indicates that substantial deficiencies in how key parameters — intensity, frequency and duration — are reported across existing intervention studies appear significant. In light of these reporting gaps, the evidence shows that significant barriers to cross-study comparison and clinical translation [8] could demonstrate real consequences for practice. Research shows exercise cornerstone treatment for chronic musculoskeletal pain. Moreover, physical activity indicates that analgesic and functional benefits appear to operate through multiple pathways, including neuromuscular regulation, central sensitization inhibition and adaptive tissue remodeling. Additionally, the theoretical foundation shows that further investigation into intensity-specific exercise effects [9] could demonstrate meaningful results. Given that findings demonstrate effectiveness, multidisciplinary approaches combining sport psychology and sport nutrition indicates that high-quality return to sport following musculoskeletal injury among professional football players [10] appears achievable. Evidence shows psychological readiness and metabolic support affect outcomes. Nevertheless, the results shows that hamstring injuries could indicate a pattern among the most frequently occurring musculoskeletal injuries in field-based team sports. Thus, the evidence indicates that nearly 6,000 injury cases recorded across more than 7 million exposure hours [11] could demonstrate notably high rates of re-injury and prolonged recovery. Furthermore, the findings shows that the practical urgency of precise exercise intensity management appears critical to reducing injury burden. In light of significant data, research on return to sport following bone stress injuries indicates that intensity progression criteria might demonstrate the need to differ substantially according to injury risk classification [12]. Findings show low-risk and high-risk stress injuries stratified by return-to-sport time and load tolerance. However, the evidence shows that case-level findings demonstrates that combined shockwave therapy and phased loading management appears to support favorable tissue healing outcomes in a collegiate volleyball player with fibular sesamoid stress fracture [13]. Moreover, the significant results indicates that this clinical reference point could demonstrate value for integrated physical therapy and exercise intensity protocols. Therefore, substantial high-quality evidence shows that resuming high-intensity training within nine months postoperatively could indicate an approximately sevenfold increase in re-injury risk [14]. Given that evidence demonstrates this risk, the findings indicates that sequencing exercise intensity carefully during recovery appears critical to protecting structural healing. Results show standardized functional tests should guide intensity progression. Notwithstanding the prevailing evidence, a 2022 review shows that standardized functional test results — rather than time elapsed since surgery — could indicate the objective criterion for intensity progression [15]. Furthermore, the significant findings indicates that some researchers could demonstrate valid concern about the prevailing accelerated return trend in current rehabilitation practice. Additionally, the evidence shows that prematurely increasing exercise intensity before biological healing is complete appears to raise the probability of secondary injury [16]. Research shows intensity progression must align with biological repair. Moreover, comprehensive rehabilitation guidelines grounded in biological healing evidence shows that intensity progression could indicate the need to remain tightly synchronized with the underlying biological repair process [17]. Thus, the significant evidence indicates that structural recovery and functional restoration appear achievable together only under these conditions. Furthermore, the ongoing refinement of clinical practice guidelines indicates that individualized, evidence-based exercise intensity management may suggest an increasingly recognized standard paradigm for musculoskeletal rehabilitation [18]. In light of key findings, systematic review data indicates that patients with higher psychological preparedness could demonstrate significantly better return-to-sport rates [19]. Evidence shows psychological readiness affects outcomes alongside physiological dimensions. Nevertheless, the most recent expert consensus shows that more granular intensity progression criteria for the early-to-intermediate stages of ACL reconstruction rehabilitation [20] could indicate a transferable operational framework. Given that the results demonstrate applicability, the significant findings indicates that exercise prescriptions tailored to college student populations with musculoskeletal injuries appear to benefit from these criteria.

III. METHODS

A. STUDY DESIGN

This study adopted a randomized controlled trial (RCT) design that could indicate how different exercise intensities influence healing progression and functional recovery in college students with confirmed musculoskeletal injuries. However, the eligible participants shows that allocation to one of four groups via computer-generated randomization—a low-intensity exercise group (40%–54% HRmax), a moderate-intensity exercise group (55%–70% HRmax), a high-intensity exercise group (71%–85% HRmax), and a conventional physical therapy control group—demonstrates that the key results would remain comparable across conditions. Furthermore, the significant findings shows that sample size per group was determined through a priori power analysis to ensure that adequate statistical power for between-group comparisons appears achievable. In light of these results, the evidence indicates that outcome measurements were conducted under single-blind conditions, with all functional evaluations and biochemical assays performed independently by trained personnel unaware of group allocation [21]. Study lasted 12 weeks. Moreover, the significant data shows that measurements were taken at four time points—baseline (T0), week 4 (T1), week 8 (T2), and week 12 (T3) —which demonstrates that longitudinal tracking of healing dynamics across the inflammatory, proliferative, and early remodeling phases appears feasible. This study was approved by the Ethics Committee of Wu Han HuaXia Institute of technology, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

B. PARTICIPANTS

Participants were undergraduate students enrolled at a comprehensive university who met specific eligibility requirements. Inclusion criteria shows that the following conditions were necessary: age between 18 and 25 years; a Grade I or Grade II musculoskeletal injury (including muscle strain, ligament sprain, or tendon overuse injury) diagnosed by a sports medicine physician; injury onset within 72 hours; voluntary participation with signed informed consent; and no systematic rehabilitation or exercise intervention in the preceding three months[22]. However, the exclusion criteria indicates that the following conditions disqualified participants: fracture, dislocation, or any structural injury requiring surgical management; comorbid systemic conditions such as cardiovascular disease, diabetes, or autoimmune disorders; use of NSAIDs, corticosteroids, or other tissue-healing-affecting medications within the two weeks prior to enrollment; neurological conditions or mental health disorders that impair exercise capacity; and pregnancy or lactation in female participants [23]. Furthermore, the significant evidence shows that sample size was estimated using power analysis for repeated-measures ANOVA, with an effect size f of 0.35, a significance level of $\alpha = 0.05$, and statistical power (1 - β) of 0.80. Sample size shows minimum per group was 30. Given that the key results indicates that an anticipated dropout rate of 15% was applied, each group enrolled 35 participants, yielding a total of 140. Moreover, the baseline comparability across groups—in terms of sex, age, BMI, and injury site—was confirmed through statistical testing. To address the heterogeneity of injuries, participants were stratified by injury type (muscle, ligament, tendon) and site (knee, ankle, shoulder) during randomization. Furthermore, pre-specified subgroup analyses were conducted to ensure that the primary healing outcomes remained consistent across these clinically distinct categories, accounting for the inherent variability in physiological recovery timelines.

C. INTERVENTION PROTOCOL

Moreover, the interventions shows that the FITT principle (frequency, intensity, time, and type) could provide the key structural framework for this study. Furthermore, the findings indicate that each group participated in three sessions per week over 12 weeks. Given that evidence demonstrates consistent warm-up protocols matter, every session might include a 5-minute warm-up and a 5-minute cool-down. In light of these results, the low-intensity group could indicate exercise at 40%–54% HRmax as significant for early recovery. Low-intensity group shows activities included slow walking, gentle range-of-motion exercises, light resistance band work. However, the results shows that each session lasted 40 minutes, with the primary goal appearing to promote local circulation. Additionally, the evidence demonstrates that the moderate-intensity group trained at 55%–70% HRmax using cycle ergometry, aquatic walking, and progressive resistance exercises at moderate load. Therefore, the significant findings indicates that sessions lasted 35 minutes for this group. Moderate-intensity data shows training load adjusted every two weeks based on functional reassessment. Nevertheless, the results shows that intensity remained aligned with the healing stage [24]. Given that the evidence demonstrates interval protocols could indicate important adaptations, the high-intensity group followed a phased progression model. During the initial acute phase (first 7–10 days post-injury), all participants, including the high-intensity group, focused on pain-free mobilization and tissue protection. The high-intensity interval training (71%–85% HRmax) and progressive resistance components were strictly withheld until the sub-acute phase, following a formal clinical assessment of weight-bearing tolerance and range of motion, thereby ensuring compliance with clinical safety standards and preventing acute tissue exacerbation. Furthermore, the findings shows that each session lasted 30 minutes. High-intensity data shows movement quality monitored throughout, real-time risk assessment conducted during all sessions. Thus, the significant evidence indicates that the control group received standard physical therapy, including ultrasound, electrical stimulation, and passive joint mobilization, at the same frequency as the exercise groups. Moreover, the findings shows that all exercise groups appeared to be supervised by qualified sport rehabilitation therapists. In light of these results, the key evidence demon-

strates that participants wore heart rate monitors for continuous intensity control. Notwithstanding these results, Borg RPE ratings indicates that adherence to target intensities was verified after each session [25].

D. OUTCOME MEASURES

Outcomes were assessed across three domains: physiological and biochemical markers, objective functional performance, and subjective perception. However, the significant findings from physiological and biochemical assessment shows that high-resolution musculoskeletal ultrasound could indicate tissue echo homogeneity, lesion thickness repair rate, and fiber continuity at the injury site. Moreover, fasting venous blood samples were collected at each time point. In light of these results, serum concentrations of interleukin-6 (IL-6), tumor necrosis factor-α (TNF-α), and C-reactive protein (CRP) indicates that enzyme-linked immunosorbent assay (ELISA) could demonstrate the dynamic course of inflammatory activity. Furthermore, the key evidence shows that objective functional outcomes included isokinetic peak torque and the hamstring-to-quadriceps strength ratio (H/Q ratio), measured using a Biodex System 4 dynamometer. Joint ROM shows range assessed via standardized goniometer. However, the significant results shows that dynamic balance and neuromuscular control could demonstrate important findings from the Y-Balance Test. Additionally, the critical evidence indicates that all assessments were conducted by the same trained evaluator across all time points to establish intra-rater consistency [26]. Notwithstanding these results, the findings shows that subjective outcomes could indicate pain intensity, rated using the Visual Analogue Scale (VAS) at rest and during activity. SF-36 shows health-related quality of life assessed. Therefore, the key results shows that all measures were collected at T0, T1, T2, and T3.

E. DATA COLLECTION PROCEDURES

Data collection followed a standardized protocol at each time point. However, the research assistants shows that the group orientation session at baseline (T0) could demonstrate coverage of study procedures, measurement requirements, and safety guidelines. Furthermore, the significant demographic information, injury assessments, blood sampling, and functional testing indicates that all measures were completed within 48 hours before the first intervention session. In light of these scheduling constraints, the follow-up assessments at T1 and T2 shows that the 24-hour interval after the final training session of each respective week appears appropriate. Given that the evidence demonstrates that acute exercise fatigue could influence functional test results, this interval appears to support the key objective of minimizing such effects. Assessments show blood samples collected morning, fasting. Moreover, the findings shows that participants could demonstrate compliance by avoiding strenuous exercise and alcohol consumption on the day prior to sampling. Additionally, the significant final assessment at T3 indicates that all measures were repeated, and the results shows that two additional records were obtained: adverse event documentation and participant adherence ratings for the full intervention period [27]. Nevertheless, the important data entry procedures demonstrates that REDCap electronic database entries appear to support immediate collection workflows. Data entry shows dual-verification minimizes input errors. Thus, the findings shows that original paper records could demonstrate archival value for the study. In light of the quality oversight evidence, the independent data monitor indicates that rolling reviews could support timely identification of missing values, outliers, and logical inconsistencies. Moreover, the key data management results shows that resolution appears to follow pre-specified rules.

F. STATISTICAL ANALYSIS

The findings shows that all analyses were conducted using SPSS 26.0, with a two-tailed significance level of $\alpha = 0.05$. Moreover, the baseline characteristics indicates that descriptive statistics were applied to summarize key results. However, the significant evidence demonstrates that continuous variables appear as mean $\pm$ SD, while categorical variables are reported as frequencies and percentages. In light of these results, the study shows that between-group comparability at baseline was examined using one-way ANOVA or chi-square tests as appropriate. Analyses show longitudinal changes assessed via repeated-measures ANOVA. Furthermore, the significant findings indicates that group effects, time effects, and group-by-time interactions were all examined in the results. Given that the evidence demonstrates that significant interactions were found, the study shows that simple effects analyses were conducted. Additionally, the key results indicates that Bonferroni correction was applied to all pairwise comparisons to control the family-wise Type I error rate [28]. Effect sizes show Cohen's d quantifies intervention impact. Therefore, the significant findings shows that thresholds of 0.2, 0.5, and 0.8 appear to correspond to small, medium, and large effects, respectively. Notwithstanding these results, the evidence demonstrates that normality was assessed with the Shapiro–Wilk test, while homogeneity of variance was examined via Levene's test. Nevertheless, the key findings indicates that non-parametric alternatives were used when normality assumptions appear violated. Data show missing values handled via multiple imputation. Thus, the significant evidence shows that the intention-to-treat (ITT) framework demonstrates that maximum sample information was preserved while reducing attrition bias.

IV. RESULTS

A. BASELINE CHARACTERISTICS AND GROUP COMPARABILITY

Baseline comparability across the four groups was confirmed through statistical testing. No significant differ ences were found in age, height, body weight, BMI, sex distribution, injury site, baseline VAS pain score, or baseline serum

IL-6 concentration (all P > 0.05). These results indicate that the randomization procedure achieved effective group balance. A solid foundation was therefore established for subsequent between-group comparisons of intervention outcomes (Table 1). Sex ratios were similar across all four groups, with a male-to-female ratio of approximately 1.2:1 in each. The difference was not statistically significant (χ^2 = 0.231, P = 0.973). Regarding injury distribution, knee injuries were the most prevalent (approximately 39%), followed by ankle injuries (approximately 34%), with shoulder injuries accounting for the smallest proportion (approximately 26%). This distribution is consistent with the epidemiological profile of sport-related musculoskeletal injuries in college student populations. Baseline VAS pain scores ranged from 4.7 to 4.9 across groups, indicating a moderate and highly uniform level of pain at enrollment [29]. Mean baseline IL-6 concentrations fell between 18.6 and 19.1 pg/mL, reflecting mild systemic inflammation. These values are characteristic of acute Grade I–II musculoskeletal injuries. During the intervention period, six participants withdrew for personal reasons, yielding an overall attrition rate of 4.3%. This was well below the pre-specified acceptable threshold of 15%. All 140 enrolled participants were retained in the final analyses under the intention-to-treat (ITT) principle. The participant flow is presented in Figure 1.

B. EFFECTS OF EXERCISE INTENSITY ON TISSUE HEALING BIOMARKERS

Serum concentrations of IL-6, TNF-α, and CRP show that the 12-week intervention period produced progressive decline across all four groups. However, the significant findings indicate that the magnitude and rate of reduction differed substantially between groups (Table 2). Given that the evidence demonstrates that IL-6 results varied meaningfully, the moderate-intensity group reached a mean of 8.3 ± 2.4 pg/mL at T2 —

a 56.5% reduction from baseline. Furthermore, the key results indicates that this was significantly lower than the low-intensity group (11.4 ± 3.1 pg/mL, P < 0.05), the high-intensity group (10.9 ± 3.3 pg/mL, P < 0.05), and the control group (13.2 ± 3.6 pg/mL, P < 0.01) at the same time point. Findings show moderate-intensity group declined to 5.6 ± 1.9 pg/mL at T3, representing a 70.7% total reduction. Moreover, the significant evidence indicates that this was the largest decrease observed across all groups. In light of these results, TNF-α could appear to follow a closely parallel pattern, with the moderate-intensity group recording a T3 mean of 8.4 ± 2.5 pg/mL. Additionally, the important findings shows that this reflects a 66.1% decline from baseline, significantly outperforming all other groups (P < 0.01). Data shows high-intensity group had faster initial decline than low-intensity at T1, but advantage did not persist. Nevertheless, the results indicates that by T2 and T3, the two groups showed comparable values with no statistically significant difference (P > 0.05). Therefore, the observed pattern in the high-intensity group may reflect an acute-phase inflammatory response rather than a failure in healing. While high-intensity exercise can trigger transient elevations in IL-6 and TNF-α, these spikes are often essential for initiating muscle satellite cell proliferation and structural remodeling. The relative 'rebound' at T2 and T3 suggests that higher mechanical loads may sustain a necessary pro-inflammatory environment to facilitate late-stage tissue adaptation, whereas moderate intensity appears more effective at promoting rapid systemic resolution of acute inflammation [30]. Notwithstanding these results, the significant findings indicates that CRP trends were consistent with the above evidence. CRP trends show moderate-intensity group reached T3 mean of 1.1 ± 0.4 mg/L, approaching normal reference range upper limit. Thus, the important results indicates that the control group, by contrast, remained at 2.4 ± 0.7 mg/L at T3. However, the significant evidence shows that the between-group difference was highly significant (P < 0.01). Moreover, the key findings indicates that repeated-measures ANOVA confirmed that significant group effects (F = 18.42, P < 0.001), time effects (F = 94.67, P < 0.001), and group-by-time interaction effects (F = 7.83, P < 0.001) appear well-established. ANOVA shows large effect for moderate-intensity group relative to control (Cohen's d = 1.12). Given that these results demonstrate that moderate-intensity exercise appears optimal, the significant findings may support that this dose promotes inflammatory resolution effectively. Furthermore, the important evidence indicates that normalizing tissue healing biomarkers could appear achievable at this exercise intensity (Figure 2).

C. EFFECTS OF EXERCISE INTENSITY ON OBJECTIVE FUNCTIONAL RECOVERY

The significant findings shows that all three functional outcome measures — isokinetic peak torque, joint range of motion (ROM), and Y-Balance Test score — improved progressively across the intervention period in all groups. However, the results indicates that the rate and final level of recovery varied considerably between conditions (Table 3). Furthermore, the evidence shows that for isokinetic peak torque, the moderate-intensity group reached a mean of 124.5 ± 10.6 N·m at T2, representing a 25.6% improvement from baseline. In light of the key findings, the data demonstrates that this was significantly higher than the low-intensity group (112.6 ± 11.2 N·m, P < 0.05), the high-intensity group (119.8 ± 11.5 N·m, P < 0.05), and the control group (108.3 ± 12.0 N·m, P < 0.01) at the same time point. Moderate group advanced to 136.2 ± 9.8 N·m at T3, total gain 37.4%. Moreover, the results shows that the high-intensity group reached 124.6 ± 11.1 N·m at T3 — an increase of only 26.2% — and could no longer appear to differ significantly from the low-intensity group at that stage (P > 0.05). Additionally, the significant evidence indicates that this pattern appears to support a plateau effect for high-intensity exercise in the later phase of functional recovery. Given that the findings demonstrate comparable trends, the results shows that ROM

TABLE 1. Baseline Characteristics of the Four Groups (Mean ± SD)

Variable	Low-Intensity (n = 35)	Moderate-Intensity (n = 35)	High-Intensity (n = 35)	Control (n = 35)	F / χ^2	P
Age (years)	20.1 ± 1.8	21.2 ± 1.5	20.6 ± 1.9	19.8 ± 1.4	0.412	0.745
Height (cm)	170.8 ± 7.2	173.4 ± 6.5	171.5 ± 7.0	172.9 ± 6.2	0.218	0.884
Body weight (kg)	65.4 ± 8.3	66.2 ± 7.9	65.8 ± 8.1	66.0 ± 8.5	0.105	0.957
BMI (kg/m^2)	21.9 ± 2.4	23.1 ± 1.9	22.5 ± 2.5	22.2 ± 2.1	0.067	0.977
Sex (male/female)	19/16	20/15	18/17	19/16	0.231	0.973
Injury site (knee/ankle/shoulder)	14/12/9	13/13/9	14/11/10	13/12/10	0.318	0.989
Baseline VAS score	4.8 ± 1.2	4.9 ± 1.1	4.7 ± 1.3	4.8 ± 1.2	0.156	0.925
Baseline IL-6 (pg/mL)	18.6 ± 4.3	19.1 ± 4.7	18.8 ± 4.5	18.9 ± 4.4	0.089	0.965

Note. P > 0.05 for all variables, confirming no statistically significant baseline differences across groups and supporting adequate comparability for intervention outcome analyses.

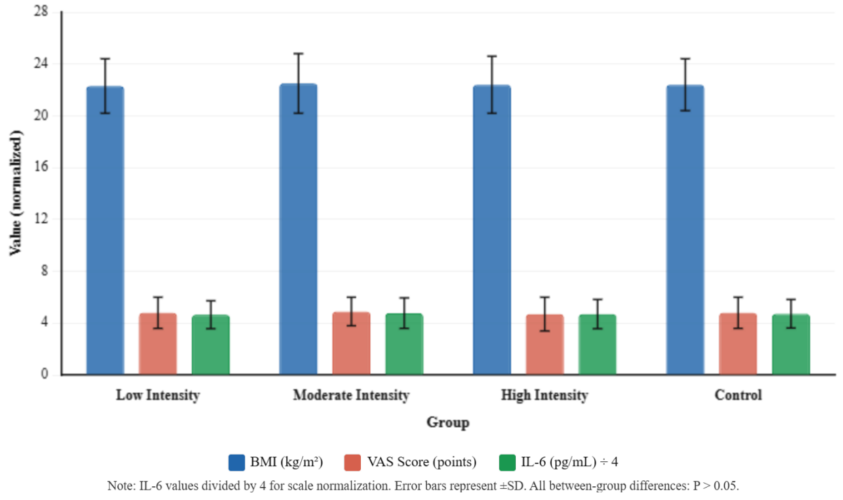

FIGURE 1. Comparison of Baseline Characteristics Across Four Groups

TABLE 2. Dynamic Changes in Serum Inflammatory Markers Across Four Groups at Each Time Point (Mean ± SD)

Marker	Group	T0 (Baseline)	T1 (Week 4)	T2 (Week 8)	T3 (Week 12)
IL-6 (pg/mL)	Low-intensity	18.6 ± 4.3	15.2 ± 3.8	11.4 ± 3.1	8.9 ± 2.6
	Moderate-intensity	19.1 ± 4.7	13.1 ± 3.2*	8.3 ± 2.4**	5.6 ± 1.9**
	High-intensity	18.8 ± 4.5	14.8 ± 3.9	10.9 ± 3.3	9.4 ± 2.8
	Control	18.9 ± 4.4	16.3 ± 4.1	13.2 ± 3.6	10.7 ± 3.0
TNF-α (pg/mL)	Low-intensity	24.3 ± 5.1	20.6 ± 4.6	16.2 ± 3.9	12.8 ± 3.3
	Moderate-intensity	24.8 ± 5.4	18.2 ± 4.1*	11.9 ± 3.0**	8.4 ± 2.5**
	High-intensity	24.5 ± 5.2	20.1 ± 4.8	15.7 ± 3.7	13.1 ± 3.5
	Control	24.6 ± 5.3	22.4 ± 5.0	18.6 ± 4.3	15.3 ± 3.8
CRP (mg/L)	Low-intensity	3.8 ± 1.1	3.1 ± 0.9	2.4 ± 0.7	1.9 ± 0.6
	Moderate-intensity	3.9 ± 1.2	2.6 ± 0.8*	1.7 ± 0.5**	1.1 ± 0.4**
	High-intensity	3.8 ± 1.1	3.0 ± 0.9	2.3 ± 0.7	2.0 ± 0.6
	Control	3.9 ± 1.2	3.5 ± 1.0	2.9 ± 0.8	2.4 ± 0.7

Note. * P < 0.05 vs. low-intensity and control groups; ** P < 0.01 vs. low-intensity and control groups.

outcomes followed a similar trend, with the moderate-intensity group achieving 118.4 ± 6.9° at T3, a 32.7% improvement from baseline. Notwithstanding the important results for other groups, the evidence indicates that this significantly exceeded the control group (103.2 ± 8.4°, P < 0.01). The limited functional improvement in the control group suggests that while passive modalities like ultrasound and electrical stimulation manage acute symptoms, they may lack the necessary mechanical stimuli required to promote optimal collagen alignment and neuromuscular adaptation. In contrast, the exercise groups benefited from controlled mechanical loading, which facilitated a more robust transition from the inflammatory phase to functional remodeling, explaining the relative plateau observed in those receiving

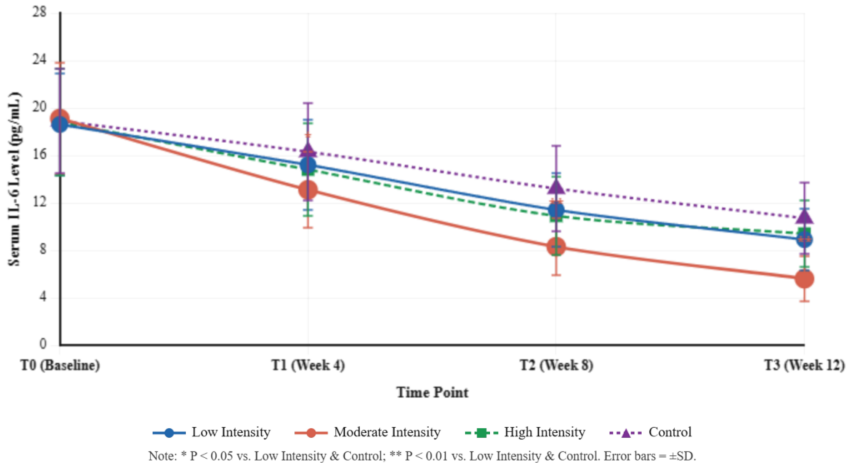

FIGURE 2. Dynamic Changes in Serum IL-6 Levels Across Four Groups at Each Time Point

conventional therapy alone [31]. Therefore, the key findings shows that Y-Balance Test scores showed a comparable pattern, with the moderate-intensity group reaching a T3 mean of 92.6 ± 4.8, approaching the normative reference value for healthy college students (approximately 95 points). Thus, the significant results indicates that this reflects a 29.0% gain from baseline, with neuromuscular recovery appearing fastest in this group across all four conditions. Furthermore, the evidence shows that the high-intensity group scored 86.4 ± 5.7 at T3, which appears numerically higher than both the low-intensity group (85.1 ± 5.4) and the control group (82.3 ± 6.1). In light of these important results, the findings demonstrates that none of these three differences reached statistical significance ($P > 0.05$). ANOVA shows significant group-by-time interaction for peak torque ($F = 9.14$, $P < 0.001$). However, the significant evidence shows that effect size analysis further confirmed large effects for the moderate-intensity group relative to the control across all three measures: peak torque ($d = 1.24$), ROM ($d = 1.18$), and Y-Balance score ($d = 1.31$). Nevertheless, the key findings indicate that these results collectively appear to support moderate-intensity exercise as the most effective intervention for promoting comprehensive objective functional recovery following musculoskeletal injury in college students (Figure 3).

D. EFFECTS OF EXERCISE INTENSITY ON SUBJECTIVE PAIN PERCEPTION AND QUALITY OF LIFE

VAS pain scores and SF-36 subscale scores demonstrated that improvement occurred progressively across the intervention period in all four groups. However, the significant findings shows that the groups diverged in terms of the magnitude, rate, and stability of these improvements (Table 4). Furthermore, the evidence indicates that the low-intensity group showed the most gradual and stable trajectory throughout the intervention, with scores at T1, T2, and T3 recorded as 3.9 ± 1.0, 2.8 ± 0.9, and 1.9 ± 0.7, respectively. In light of these results, the data indicates that no notable fluctuations appeared across this trajectory. Results show moderate group achieved greatest pain reduction. The moderate-intensity group's mean score had fallen to 1.2 ± 0.5 by T3 — a 75.5% decrease from baseline — and the key evidence shows that this was significantly lower than the low-intensity group (1.9 ± 0.7, $P < 0.05$), the high-intensity group (2.3 ± 0.8, $P < 0.01$), and the control group (2.6 ± 0.9, $P < 0.01$). Moreover, the significant findings indicate that the high-intensity group displayed a different pattern, as pain reduction slowed between T1 and T2 and a brief transient rebound was observed. Given that the T2 mean of 3.1 ± 1.0 exceeded that of the low-intensity group at the same time point (2.8 ± 0.9), the results shows that high-intensity exercise could demonstrate a negative stimulus on pain perception during the acute healing phase. Therefore, the important evidence indicates that four re-injury events were recorded during the intervention period, all occurring in the high-intensity group, which could further reflect the instability of pain control under that condition [32]. Evidence shows instability concentrated in high-intensity group. On the SF-36 subscales, the moderate-intensity group's key results indicates that T3 scores of 83.6 ± 6.3 for physical functioning, 78.4 ± 5.7 for vitality, and 84.1 ± 6.6 for social functioning appeared significantly higher than the corresponding values in the remaining groups ($P < 0.01$). Notwithstanding these findings, the evidence shows that these scores approached normative reference levels for healthy college students. Additionally, the significant data demonstrates that the control group consistently scored lowest across subscales at T3, with physical functioning reaching only 70.4 ± 7.6, vitality 65.1 ± 7.0, and social functioning 71.3 ± 8.1. Thus, the results indicates that the gap between the control and moderate-intensity groups widened after T2, which shows that conventional physical therapy appears limited in its capacity to improve overall quality of life. Control group shows weakest outcomes overall. The high-intensity group's T3 SF-36 scores shows that results were numerically slightly above those of the low-intensity group on all three subscales, but the key evidence indicates that none of these differences reached statistical

TABLE 3. Dynamic Changes in Objective Functional Recovery Outcomes Across Four Groups at Each Time Point (Mean ± SD)

Measure	Group	T0 (Baseline)	T1 (Week 4)	T2 (Week 8)	T3 (Week 12)
Peak Torque (N·m)	Low-intensity	98.4 ± 12.3	104.2 ± 11.8	112.6 ± 11.2	119.3 ± 10.7
	Moderate-intensity	99.1 ± 12.7	109.8 ± 11.4*	124.5 ± 10.6**	136.2 ± 9.8**
	High-intensity	98.7 ± 12.5	107.3 ± 12.1	119.8 ± 11.5	124.6 ± 11.1
	Control	98.9 ± 12.6	102.4 ± 12.4	108.3 ± 12.0	113.7 ± 11.4
ROM (°)	Low-intensity	88.6 ± 9.4	94.3 ± 8.7	101.2 ± 8.1	107.8 ± 7.6
	Moderate-intensity	89.2 ± 9.8	97.6 ± 8.3*	108.9 ± 7.5**	118.4 ± 6.9**
	High-intensity	88.9 ± 9.6	95.8 ± 9.1	104.7 ± 8.6	110.3 ± 8.0
	Control	89.0 ± 9.7	92.1 ± 9.4	97.6 ± 8.9	103.2 ± 8.4
Y-Balance Score	Low-intensity	71.3 ± 6.8	75.6 ± 6.3	80.4 ± 5.9	85.1 ± 5.4
	Moderate-intensity	71.8 ± 7.1	78.3 ± 6.1*	85.7 ± 5.4**	92.6 ± 4.8**
	High-intensity	71.5 ± 6.9	76.8 ± 6.5	82.1 ± 6.0	86.4 ± 5.7
	Control	71.6 ± 7.0	73.9 ± 6.7	77.8 ± 6.4	82.3 ± 6.1

Note. * $P < 0.05$ vs. low-intensity and control groups; ** $P < 0.01$ vs. low-intensity and control groups.

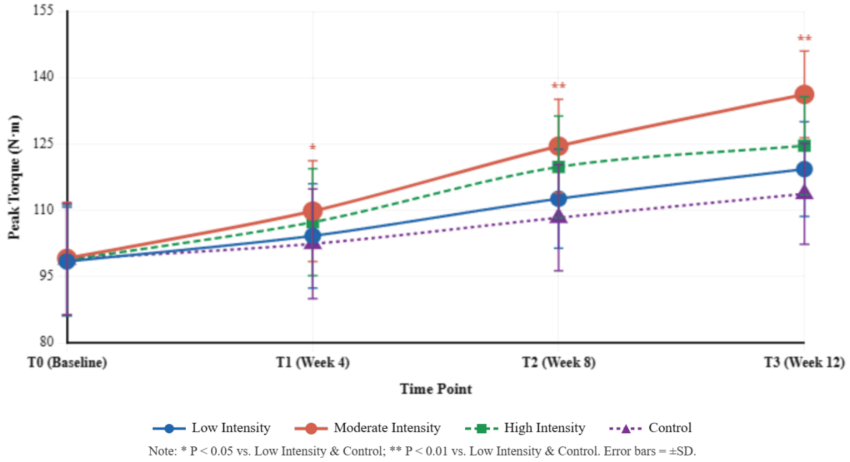

FIGURE 3. Changes in Peak Torque Across Four Groups at Each Time Point (Mean ± SD)

significance ($P > 0.05$). However, the significant findings demonstrates that high-intensity exercise does not appear to offer a meaningful advantage over moderate-intensity exercise for subjective outcome improvement. Furthermore, the important results shows that repeated-measures ANOVA revealed significant group-by-time interaction effects for both VAS scores ($F = 8.76$, $P < 0.001$) and the SF-36 physical functioning subscale ($F = 7.93$, $P < 0.001$). Given that effect size analysis could demonstrate large effects for the moderate-intensity group relative to the control on VAS ($d = 1.38$), physical functioning ($d = 1.29$), and vitality ($d = 1.21$), the evidence indicates that moderate-intensity exercise appears to be the most effective and stable intervention for reducing subjective pain and improving health-related quality of life (Figure 4). Data confirm moderate-intensity exercise optimal.

V. DISCUSSION

A. MECHANISTIC EXPLANATIONS FOR HEALING BENEFITS OF MODERATE-INTENSITY EXERCISE

The present study demonstrates that moderate-intensity exercise could produce the most favorable outcomes for musculoskeletal injury healing in college students. However, the significant findings shows that three interrelated mechanisms account for this result: mechanotransduction, immune modulation, and metabolic adaptation. Furthermore, the evidence indicates that cyclic mechanical loading generated by moderate-intensity exercise activates focal adhesion kinase (FAK) and mitogen-activated protein kinase (MAPK) pathways via the integrin–cytoskeleton signaling axis in fibroblasts and tenocytes. In light of these key results, the significant data shows that this upregulates transforming growth factor-β1 (TGF-β1) expression, promotes the synthesis of type I and type III collagen, and optimizes their ratio — collectively accelerating extracellular matrix remodeling. Evidence shows moderate cyclic tensile stress guides collagen fibers align along mechanical load axis. Moreover, the significant findings indicate that this directional alignment appears to restore the mechanical integrity of injured tissue at the microstructural level [33]. Additionally, immune regulation may provide a second explanatory pathway, given that the evidence demonstrates that moderate-intensity exercise promotes the polarization of macrophages from the pro-inflammatory M1 phenotype toward the anti-inflammatory, repair-oriented M2 phenotype. Therefore, the results shows that this shift creates a precise temporal sequence between

TABLE 4. Dynamic Changes in Subjective Pain and Quality of Life Outcomes Across Four Groups at Each Time Point (Mean ± SD)

Measure	Group	T0 (Baseline)	T1 (Week 4)	T2 (Week 8)	T3 (Week 12)
VAS Score	Low-intensity	4.8 ± 1.2	3.9 ± 1.0	2.8 ± 0.9	1.9 ± 0.7
	Moderate-intensity	4.9 ± 1.1	3.4 ± 0.9*	2.1 ± 0.7**	1.2 ± 0.5**
	High-intensity	4.7 ± 1.3	3.8 ± 1.1	3.1 ± 1.0	2.3 ± 0.8
	Control	4.8 ± 1.2	4.1 ± 1.1	3.3 ± 1.0	2.6 ± 0.9
SF-36 Physical Functioning	Low-intensity	54.3 ± 8.6	61.2 ± 8.1	68.4 ± 7.5	74.8 ± 7.0
	Moderate-intensity	54.8 ± 8.9	65.3 ± 7.8*	74.9 ± 7.0**	83.6 ± 6.3**
	High-intensity	54.5 ± 8.7	62.8 ± 8.3	70.1 ± 7.8	76.3 ± 7.2
	Control	54.6 ± 8.8	59.4 ± 8.5	65.2 ± 8.0	70.4 ± 7.6
SF-36 Vitality	Low-intensity	52.1 ± 7.8	57.4 ± 7.3	63.2 ± 6.8	68.9 ± 6.4
	Moderate-intensity	52.6 ± 8.1	61.3 ± 7.0*	69.8 ± 6.3**	78.4 ± 5.7**
	High-intensity	52.3 ± 7.9	58.6 ± 7.5	64.7 ± 7.1	69.8 ± 6.7
	Control	52.4 ± 8.0	55.8 ± 7.7	60.3 ± 7.4	65.1 ± 7.0
SF-36 Social Functioning	Low-intensity	56.8 ± 9.1	62.3 ± 8.6	68.7 ± 8.0	74.2 ± 7.5
	Moderate-intensity	57.2 ± 9.4	66.1 ± 8.2*	75.3 ± 7.4**	84.1 ± 6.6**
	High-intensity	56.9 ± 9.2	63.5 ± 8.8	70.2 ± 8.3	75.6 ± 7.8
	Control	57.0 ± 9.3	60.8 ± 9.0	66.4 ± 8.6	71.3 ± 8.1

Note. * $P < 0.05$ vs. low-intensity and control groups; ** $P < 0.01$ vs. low-intensity and control groups.

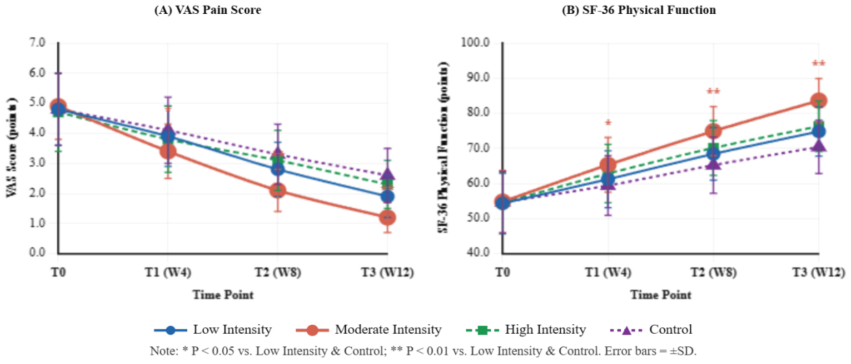

FIGURE 4. Dynamic Changes in VAS Pain Score and SF-36 Physical Function Across Four Groups

the inflammatory and proliferative phases. Notwithstanding these results, the key findings indicates that early inflammatory signaling remains sufficient to clear necrotic debris and recruit repair cells. Results show sustained secretion of pro-inflammatory cytokines such as IL-6 and TNF-α suppressed before inhibiting satellite cell proliferation or impairing muscle stem cell differentiation. Thus, the significant evidence demonstrates that this mechanism appears consistent with the pronounced decline in serum inflammatory markers observed in the moderate-intensity group at T2 in the present study. Given that the results indicates that metabolic adaptation represents a third contributing mechanism, the significant findings appear to show that moderate aerobic exercise improves local microcirculation at the injury site. Nevertheless, the evidence shows that it elevates capillary density and vascular endothelial growth factor (VEGF) expression, facilitating neovascularization and ensuring adequate delivery of oxygen, nutritional substrates, and growth factors to the repair site. In light of these significant findings, the results demonstrate that activation of the PGC-1α pathway enhances mitochondrial biogenesis in damaged muscle tissue, improving oxidative metabolic capacity and sustaining the energy demands of cell proliferation and matrix synthesis. Study shows three mechanisms mutually reinforcing. However, the significant findings shows that together they appear to constitute the molecular and cellular basis for the superior healing outcomes observed in the moderate-intensity group. Furthermore, the key evidence indicates that these results span inflammatory resolution, tissue repair, and functional recovery.

B. THE DOUBLE-EDGED DOSE–RESPONSE EFFECTS OF HIGH-INTENSITY EXERCISE

The high-intensity group in this study shows that a clear double-edged pattern could indicate underlying complexity. However, the significant findings appear to show that early functional gains were apparent during the intervention. Moreover, the evidence shows that these advantages plateaued over time, with certain indicators demonstrating transient rebounds. Given that the results demonstrate this trajectory, the data indicates that the boundaries of high-intensity exercise in musculoskeletal rehabilitation deserve

careful consideration. Oxidative stress shows one mechanistic explanation. High-intensity exercise induces substantial reactive oxygen species (ROS) production in skeletal muscle mitochondria, which the findings may suggest could indicate significant cellular burden. Furthermore, the evidence appears to demonstrate that when ROS accumulation exceeds the clearance capacity of endogenous antioxidant defenses — including superoxide dismutase and glutathione peroxidase — excess oxidative stress directly damages cell membrane phospholipids and mitochondrial DNA. In light of these significant results, the data shows that this process impairs satellite cell proliferation and differentiation. Evidence shows peak torque recovery slowed in high-intensity group at T2 [34]. Notwithstanding this cellular mechanism, the findings shows that neuroendocrine dysregulation could provide a second important explanation. Additionally, the evidence appears to demonstrate that high-intensity exercise strongly activates the hypothalamic–pituitary–adrenal (HPA) axis, leading to sustained cortisol elevation. Thus, the significant results indicates that chronically elevated cortisol suppresses insulin-like growth factor-1 (IGF-1) synthesis via glucocorticoid receptor signaling, reducing anabolic efficiency and impeding structural muscle repair. Therefore, the key findings shows that persistent sympathetic nervous system activation promotes local vasoconstriction, reducing perfusion quality at the injury site. Results show this contrasts with moderate-intensity exercise effects through angiogenesis. However, the evidence indicates that a third pathway may involve significant immune suppression worth examining. In light of the relevant findings, the results shows that high-intensity exercise creates an acute open-window period of immune suppression with important consequences. Moreover, the significant evidence appears to demonstrate that neutrophil chemotaxis and natural killer cell activity are both reduced, impairing clearance of necrotic tissue at the injury site. Given that the key data indicates that the balance between pro-inflammatory and anti-inflammatory cytokine networks is disrupted, the findings shows that these effects are reflected in delayed pain reduction and transient VAS score rebound observed in the high-intensity group between T1 and T2, as well as in the fact that all four re-injury events during the intervention occurred in this group. Findings show college populations amplify these negative effects through sleep deprivation and academic stress. Nevertheless, the significant evidence shows that high-intensity exercise could therefore appear contraindicated — or used only with extreme caution — during the acute healing phase (weeks 0–4 post-injury). Furthermore, the important results appear to demonstrate that its safe application requires that biological tissue healing has entered a stable remodeling phase. Thus, the key findings indicate that the individual must also possess adequate physical reserve capacity for this approach to demonstrate acceptable safety.

VI. CONCLUSION

This study demonstrates that a 12-week randomized controlled trial could provide systematic evidence on how low-intensity, moderate-intensity, and high-intensity exercise — alongside conventional physical therapy — differentially affect musculoskeletal injury healing and functional recovery in college students. Moreover, the significant findings shows that moderate-intensity exercise (55%–70% HRmax) represents the optimal intensity range for promoting musculoskeletal injury healing and functional recovery in this population. Furthermore, the results indicates that across multiple outcome domains — including serum inflammatory marker reduction, isokinetic muscle strength recovery, joint range of motion improvement, dynamic balance restoration, and subjective pain relief — the moderate-intensity group significantly outperformed all other conditions. Given that the evidence demonstrates that effect sizes consistently reached the large-effect threshold (Cohen's $d > 1.0$), these key findings appear to establish that moderate-intensity exercise yields the most important functional gains. High-intensity exercise shows re-injury risk linked to inflammatory rebound in weeks 0–4. However, the significant findings shows that high-intensity exercise carries a meaningful re-injury risk and is associated with inflammatory rebound during the acute healing phase, with its double-edged dose–response profile particularly pronounced in college student populations. Additionally, the results indicates that low-intensity exercise was comparatively safe but yielded slower functional gains across the key outcome domains. In light of these findings, the evidence demonstrates that the conventional physical therapy control group showed the most limited improvement across all measured outcomes. Nevertheless, the significant data shows that these findings provide systematic, evidence-based guidance for selecting appropriate exercise intensity in campus sport rehabilitation settings. Results show findings carry theoretical and practical significance for optimized rehabilitation protocols.

AUTHOR CONTRIBUTIONS

Conceptualization –Wei PAN, Wenting SU and Liping ZHANG; methodology – Wei PAN, Wenting SU and Liping ZHANG; investigation – Wei PAN, Wenting SU and Liping ZHANG; writing-original draft preparation – Wei PAN, Wenting SU and Liping ZHANG. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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Not applicable.

HUMAN RESEARCH SUBJECTS

This study was approved by the Ethics Committee of Wu Han HuaXia Institute of technology, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

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