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Effects of Neuromuscular Reeducation on Hip Mechanics and Functional Performance in Patients after Total Hip Arthroplasty: A Case Series

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Abstract

Background—Following total hip arthroplasty, patients demonstrate compensatory movement strategies during activities of daily living such as walking and stair climbing. Movement compensations are important markers of functional decline in older adults and are related to poor functional capacity. Despite increased utilization of hip arthroplasty, persistent movement compensation, and functional performance deficits, no consensus on postoperative rehabilitation exists. Neuromuscular reeducation techniques offer a strategy to improve movement quality by emphasizing hip abductor performance and pelvic stability. This case series illustrates changes in movement strategy around the hip in response to targeted neuromuscular reeducation techniques after hip arthroplasty.

Methods—Five participants received an 8-week exercise program following total hip arthroplasty, emphasizing targeted neuromuscular reeducation techniques hallmarked by specific, weight-bearing exercise to improve hip abductor performance and pelvic stability. Five additional participants were supervised and followed for comparison.

Findings—Participants in the neuromuscular reeducation program improved their internal hip abductor moments and vertical ground reaction forces during walking and stair climbing. They also improved their functional performance and hip abductor strength outcomes.

Interpretation—Targeted neuromuscular reeducation techniques after total hip arthroplasty provided a positive effect on biomechanical outcomes, functional performance, and muscle strength. Through focused use of the hip abductor muscles, increased internal hip abductor moments were observed. This intervention potentially promotes pelvic stability, and may contribute to improved performance on tasks such as stair climbing, fast walking, and balance.

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The results suggest that neuromuscular reeducation offers a unique effect on movement strategy and function for patients following total hip arthroplasty.

Keywords

Hip Arthroplasty; Gait Mechanics; Neuromuscular Reeducation; Rehabilitation

Introduction

Total hip arthroplasty (THA) has become one of the most common orthopedic surgeries.¹ In the next 15 years, the THA surgery rate in the United States is expected to increase by 174%, to more than 500,000 per year.^{2,3} Despite the increase in utilization of THA, there is no consensus for rehabilitation exercise guidelines after THA.⁴ Exercise following THA can safely improve physical function and strength outcomes following THA.^{1,5-9} However, variable approaches to timing of initiation, mode, and dose of exercise has led to a lack of agreement on optimal exercise prescription following THA.¹ Moreover, existing exercise studies have not focused on the persistent movement compensations observed after THA.

Compensatory movement strategies, such as asymmetrical limb loading,¹⁰ asymmetrical power production and muscle activation,¹¹ and ipsilateral lumbar side bending combined with decreased hip abduction moment,¹² have been observed in patients after unilateral THA during daily activity,¹⁰ walking,^{12,13} and stair climbing.¹¹ These movement compensations may relate to poor physical function after THA. In particular, abnormal muscle control at the hip and pelvis during gait, which often results in an abnormal gait pattern, is indicative of low internal hip abduction moments which are related slow walking speeds observed after THA.^{12,14-16} Some investigations suggest that walking mechanics never return to normal following THA.¹⁷ Movement compensations have been found to serve as important biomarkers of functional decline in a variety of older adult populations^{18,19} and are linked to increased fall risk^{18,19} and poor functional outcomes,²⁰ thus highlighting the importance of addressing these compensations through postoperative exercise programs.

The resolution of persistent movement compensations requires targeted exercise to improve the ability of the body to produce stable, coordinated movements during functional tasks. Such exercise is clinically referred to as neuromuscular reeducation (NMR).²¹ At the hip and pelvis, stability is largely dependent on the hip abductor muscles ability to produce internal hip abduction moments to control pelvic motion during unilateral stance.^{22,23} Optimal NMR targets movement compensations by promoting coordinated hip and pelvic muscle activity and pelvic stability,²⁴ which requires integrating strength training with focused movement reeducation feedback techniques, rather than isolated strength training.²⁵ Hip abductor muscles actively respond to movement perturbations during function to maintain a stable pelvic base.²⁴ Without such pelvic stability, movement compensations occur, such as a Trendelenburg gait pattern, which may negatively impact walking performance and create difficulty performing activities of daily living that may lead to further injury.²⁶

NMR techniques can be used to target the hip abductor muscles ability to stabilize the pelvis by resisting external moments during functional tasks. NMR techniques have successfully improved strength and postural stability,^{27,28} gait kinematics,²⁹ and movement patterns, while also reducing the risk of injury in other populations such as patients with ankle injury and anterior cruciate ligament reconstruction.^{30,31} However, the efficacy of targeted NMR techniques to improve hip abductor performance, movement quality, and functional performance after THA is unknown.

The purpose of this case series was to describe the changes in movement strategy during daily tasks resulting from the use of targeted NMR techniques during postoperative THA rehabilitation. We hypothesized that NMR techniques would 1) increase the involved limb internal hip abductor moments and vertical ground reaction forces during walking and stepping compared with a typical course of care after THA and 2) improve functional performance and isometric hip abductor strength.

Methods

Participants

Ten participants were recruited from one of two area hospitals by physician referral or advertisement at preoperative educational sessions. Inclusion criteria included primary posterior approach THA for the treatment of hip osteoarthritis, aged 50–75 years. Exclusion criteria included a history of uncontrolled diabetes, body mass index $>40 \text{ kg/m}^2$, or additional orthopedic or neurologic pathology that impaired function. Five participants completed a neuromuscular reeducation exercise intervention (NMR). Additionally, five participants were supervised and followed for comparison (CON). Patients were assessed preoperatively and postoperatively, following the completion of the intervention. Testing and NMR group rehabilitation occurred within the Muscle Performance Laboratory at the University of Colorado, Anschutz Medical Campus. All participants were provided written, informed consent and this study was approved by the Colorado Multiple Institutional Review Board.

Intervention

The NMR group participated in outpatient rehabilitation 2x/week (approximately 45 minutes per session) for 8 weeks. The CON group was supervised by the study physical therapist, and advised on continuing exercise programs initiated in the hospital, but did not attend outpatient rehabilitation, which represents current practice patterns in the community.

Neuromuscular Reeducation Exercise Program—The NMR program combined strength training with focused techniques emphasizing use of the hip abductors to stabilize the pelvis, thus improving movement quality to maximize functional recovery. These techniques included specific, weight-bearing exercise aimed to improve hip abductor performance and pelvic stability. Specifically, participants progressed through bilateral, then unilateral weight-bearing tasks, which included both static and dynamic functional tasks. These activities were supervised closely by the therapist who provided verbal, visual, and tactile cues to promote pelvic stability. These techniques were also used to promote the use

of hip abductors as a means to maintain a horizontal pelvic alignment during performance of the tasks. Progression of these activities was based on the ability of the participant to achieve the desired posture and movement quality. Specifically, the participants had a band around their pelvis at the level of the anterior, superior iliac spines of the pelvis, placed by the therapist, and used a mirror to visualize ability to maintain the band, and thus the pelvis, horizontal during the task. These tasks were further progressed to more unstable surfaces, such as foam and BOSU ball, to increase task difficulty. This exercise protocol also included core stabilization exercise focusing on lower abdominal muscle training to enhance pelvic stability, and functional mobility training. Functional training progressed from basic gait training with an assistive device to agility training which included stair climbing, side stepping and carioca stepping with increasing speed. Visual, verbal, and tactile cues were provided for participants to attempt to maintain a stable, horizontal pelvis during gait and agility training activities. Finally, the NMR program included progressive, resistance strength training to remediate strength in the major hip and thigh musculature impacted by THA.³² The exercises included use of weighted pulleys and weight-training machines. Therapists determined an 8-repetition maximum for each muscle group and weight was increased by at least 10% every 2 weeks to maximize muscle hypertrophy and strength gains. The NMR program included both supervised clinic-based exercise and home exercise to maximize movement quality, muscle strength and functional performance.

Control Group Program—Participants in the CON group received weekly 30–45-minute home visits by study staff during the first 6 weeks of the intervention period and then were contacted by phone for the last 2 weeks. Participants received continued education on the exercises received during their hospital stay, such as activities to improve range of motion, flexibility and isometric muscle training, which patients typically continue independently after hospital discharge. They also received education regarding functional training and safety for activities of daily living. As there is no widely accepted standard of care for rehabilitation following THA¹ and discussions with local physical therapists within our partner hospitals indicated that patients do not routinely receive outpatient rehabilitation services, this control group closely mirrored usual postoperative care typically received in the community.

Outcomes

All outcomes were assessed preoperatively and at the completion of the intervention period. One investigator (JW) performed the biomechanical outcomes assessment including marker setup and instructions. A second investigator (DJ) instructed patients for all functional performance and muscle strength assessments using the same instructions and protocol for each patient, while a second investigator (JW) recorded all values.

Biomechanical Analysis—Biomechanical analysis was completed by one investigator (JW) overseeing all data collections. Three-dimensional joint kinematics were measured by tracking retro-reflective markers placed bilaterally on the iliac crest, greater trochanter, lateral femoral condyle, lateral malleolus, head of the 5th metatarsal, and two markers on the heel of each participant. Four rigid thermoplastic shells with four markers were used to track the movement of the thigh and shank; one thermoplastic shell with three markers was used

to track the pelvis. An 8-camera three-dimensional motion capture system (Vicon, Oxford Metrics, London, UK) was used to track marker position at 100 Hz. Two imbedded force plates (Berotec Corp., Worthington, OH, USA) were used to collect force data at 2000Hz. Motion analysis was performed during 3 different dynamic tasks: level walking, stepping up onto a wooden platform, and during the landing phase stepping off the platform. During level walking trials, participants were instructed to walk across a level walkway (13 m long) at their self-selected speed.

Following the level walking trials, participants were instructed to use their surgical limb to step up onto a wooden platform (8" in height), that was placed on a force plate, pause on the platform and then step off the wooden platform onto the 2nd force plate with their surgical limb. The height of the point of contact of the force plate was adjusted in the data acquisition software to account for the height of the step. Prior to testing, the step up and landing tasks were described and demonstrated to each participant. Participants were excluded from performing any task that they felt uncomfortable attempting or that the investigator deemed unsafe. The average of 3–5 trials was used for the analysis, depending on the physical ability of the participant at the time of the data collection.

Marker trajectories were low-pass filtered at 6 Hz and force data at 50 Hz using a second-order phase corrected Butterworth filter. A standing calibration trial was taken to identify joint centers and create the segment coordinate systems. Continuous internal hip abduction moments were calculated during each dynamic task using a standard inverse dynamics approach integrating kinematic and kinetic data using Visual 3D software (C-Motion, Germantown, MD). From the continuous hip moments, peak surgical-limb internal hip abduction moments during the single-limb stance phase of each dynamic task were quantified (Figure 1). All joint moments were normalized to the participant's body mass.

Functional Performance—Participants completed a stair climb test (SCT),³³ 4-meter walk test (4MW), the 6-minute walk test (6MW), and completed the Fullerton Advanced Balance Scale (FAB) to assess physical function. The SCT determines the time a person takes to ascend and descend 12 stairs. This valid, reliable³⁴ measure places high demand on the hip musculature during this task and was chosen to represent high-level, unilateral task commonly performed.¹¹ Participants completed the combined 12-stair ascent and descent as quickly as possible. The use of the handrail or assistive device was permitted if necessary. The 4-meter walk test measures the time to walk 4 meters validated to generate gait speed values associated with morbidity and mortality.³⁵ Participants performed the 4MW with instructions to complete the test as “quickly but as safely as possible.” The course included a two meter distance from the start line to where timing was initiated and a two meter distance to the stop line from where timing was terminated to allow acceleration and deceleration to occur. The 6-minute walk test³⁴ (6MW) assesses how far a person can walk in 6 minutes. This test is widely used to measure endurance and is a valid measure of functional mobility.^{36,37} The test was performed in a 30.5-m hallway and the total distance covered, in meters, was recorded. Finally, patients completed Fullerton Advanced Balance Scale (FAB), a valid and reliable metric for assessing static and dynamic postural control in older adults.³⁸ The FAB consists of 10 individually scored items which include both low- and high-level

balance activities. The FAB scale has high intra- and inter-rater reliability (0.92–1.00 and 0.91–0.95, respectively).³⁸

Muscle Strength—Isometric strength of the surgical limb hip abductor muscles were assessed using an electromechanical dynamometer (HUMAC NORM, CSMI Solutions, Stoughton, MA). Maximal voluntary isometric contractions (MVICs) of the surgical limb hip abductor were performed in a side-lying position with 0° of abduction/adduction and 0° of flexion/extension using a strap to stabilize the pelvis.^{39,40} Data were sampled using a BiopacData Acquisition System (MP 150 Biodex Medical Systems, Inc., Shirley, NY) and analyzed using AcqKnowledge software, Version 3.8.2 (Biodex Medical Systems). All MVIC measurements were expressed in units of torque (Nm). Each MVIC was preceded by two sub-maximal warm-up contractions. Participants were given visual targets from the dynamometer's output and strong verbal encouragement during each trial to maximize effort. The trial with the highest torque was scaled to body mass (Nm/kg) for analysis.⁴¹

Results

Descriptions of the participants are located in Table 1. All participants in the NMR group completed the 8-week intervention (16 total sessions). There were no adverse events that precluded intervention completion.

Biomechanical Outcomes

Biomechanical outcomes are presented in tables 2 and 3. Following completion of the NMR exercise program, four of the five participants increased their internal hip abduction moments during level walking. Additionally, increases in the peak vertical ground reaction force (VGRF), ranging from ~2–22%, during level walking occurred in four out of five NMR participants. During the step up task three of the five NMR participants increased their internal hip abduction moment and 2 of the 5 participants increased the peak VGRF during the step up by 2 and 12%. One participant in the NMR group who was unable to perform the step up task prior to surgery was able to perform the step up at the 10 week post-surgery assessment. Finally, during the landing task three of the five NMR subjects increased their internal hip abduction moment by ~35–1767% and peak VGRF increased by ~11–68% in four of the five NMR participants. There was one participant from the NMR group who was unable to perform the landing task prior to surgery, but successfully completed the landing task at the final assessment.

In comparison, one CON group participant had a 1.4% increase in internal hip abductor moment and no participants had an increase in peak VGRF during level walking. During the step-up task, one CON group participant had a 258% increase in internal hip abductor moment and one who had a 1.9% increase in peak VGRF. There was one participant in the CON group who was able to perform the step up during the pre-surgical assessment was unable to perform the step up at the final assessment. Finally, there was an increase in internal hip abductor moment by ~20–186% and peak VGRF by ~6–22% in three of the five CON group participants during the landing task.

Functional Performance

Functional performance outcomes are presented in Table 4. Following the 8-week intervention period, all five participants in the NMR program improved their time on the SCT by 6–44%, improved their distance walking in the 6MW test by 10–300%, and improved their FAB score from 7–64%. Further, four of the five participants in the NMR program improved their 4MW time by 9–33%.

In contrast, two of the five CON group participants improved their SCT time by 12 and 19% and 4MW time by 4 and 12%, while four of the CON group participants improved their distance walked on the 6MW test from ~6–21%. However, all five participants in the CON group performed worse on the FAB from 0–16%.

Muscle Strength

All five participants in the NMR exercise program improved their isometric hip abduction strength in the involved limb by ~20–50%. Two of the five CON group participants improved their hip abductor strength, while three of the five were weaker than preoperative levels at the end of the 8-week intervention period (Table 4).

Discussion

This case series examined biomechanical outcomes, functional performance, and muscle strength in patients after THA who participated in a targeted neuromuscular reeducation (NMR) program designed to enhance pelvic stability through hip abductor performance. The results suggest that these techniques can improve hip abductor muscle performance and use of the surgical limb as seen through improvements in internal hip abductor moments and vertical ground reaction forces measured during functional tasks. The enhanced ability to use the surgical limb observed in the NMR group likely contributed to the improved functional performance and strength outcomes also observed in the NMR group. NMR techniques may offer benefits to movement quality beyond traditional isolated strength training or functional training after THA.

Movement compensations have been found to serve as important biomarkers of functional decline in a variety of older adult populations, including increased fall risk^{18,19} and poor functional outcomes.²⁰ Following THA, persistent movement compensation strategies, such as reduced internal hip abduction moments associated with Trendelenburg compensated gait¹², asymmetrical limb loading,¹⁰ asymmetrical power production and muscle activation,¹¹ and ipsilateral lumbar side bending combined with decreased hip abduction moment¹² are common during activities of daily living. In this case series, patients with NMR training had increases in the internal hip abduction moments and peak VGRF during level walking, stepping up and landing from a step over the course of rehabilitation, indicating improved ability to use these muscles to resist external moments during activities of daily living. For example, one patient increased their internal hip abduction moments during level walking (–0.028-- –0.220 Nm/kg [685%], Table 2), stepping up (–0.109-- –0.287Nm/kg [163%], Table 3), and stepping down (–0.027-- –0.504 [1766%] Nm/kg, Table 3). These large increases in hip abduction moment demonstrate a change in movement pattern from one

requiring minimal hip abductor muscle function to a movement pattern that relied on hip abductor muscles for pelvic stability. Prior investigations have suggested that gait mechanics do not return to level of asymptomatic adults follow THA.¹⁷ The presence of improvements in gait mechanics following and NMR rehabilitation program suggest that improvements in gait mechanics can be achieved. Despite these improvements, however, the measured hip abductor moments measured in this study did approach the level of hip force measured in the previously mention study.¹⁷ Observations such as this have significant clinical implications, as increased internal hip abduction moments have been associated with decreased progression of ipsilateral knee OA.⁴² This suggests that the improvement of movement strategy and gait mechanics can effect long-term musculoskeletal health, as well as serve to maintain functional performance during aging by minimizing movement compensation.

The aforementioned changes in hip abductor moments were often not directly related to changes in muscle strength. Interestingly, the participant mentioned previously had a relatively small increase in isometric hip abductor strength (0.71–0.91 Nm/kg, ~28%, Table 2) compared to the increase in functional internal hip abduction moments, suggesting a greater improvement in movement strategy than strength with targeted NMR training. Similarly, increased hip abductor strength observed in other participants was not indicative of improved internal hip abduction moments during function. Specifically, two of the patients in our comparison group had increases in hip abductor strength without concomitant increases in internal hip abductor moments. These observations suggest that following THA, increased hip abductor strength, without focused NMR, may not necessarily translate to improved hip abductor performance and movement strategy. Utilizing a postoperative exercise program that incorporates NMR techniques appears to improve muscle performance and movement strategies during daily tasks.

The NMR exercise program in this study attempted to improve functional performance by including targeted activities to improve pelvic stability by promoting the hip abductors' ability to counter external moments during functional tasks. All participants in the NMR exercise group had improvements in stair climbing performance, 6MW distance, and FAB score, with 4 of the 5 having improved gait speed. The observed improvements were clinically important. Four of the 5 NMR patients exceeded MCID of 2.6 seconds⁴³ in the SCT, the MCID of 0.14m/s⁴⁴ for gait speed, and the MCID of 61 meters³⁷ in their 6MW distance. Additionally, all 5 NMR patients improved their FAB score to above the cut-off value for determining fall risk⁴⁵ while most patients in the CON group remained below this value. These findings are in contrast to previous work in our laboratory which demonstrated a decline in functional performance for patients receiving less than 5 visits of outpatient physical therapy during this time period after THA.³² Additional work in our laboratory with a group of asymptomatic older adults indicate that 2 of the 5 NMR patients attained the same level of function in stair climbing and 6MW distance and 3 of the 5 had similar hip abductor strength at the end of intervention as the asymptomatic group.⁴⁶ Reasons for functional improvement are likely multi-factorial, but one factor maybe the mechanical link between control of the pelvis and lower extremity function. The NMR program focused on utilizing the lateral hip musculature to stabilize the pelvis in a variety of situations, forcing the pelvis to become a stable base for movement, which is critical for producing efficient,

coordinated movement.^{24,26} Furthermore, the gluteal muscles are responsible for stabilizing the femur in response to external joint moments during movement.²⁴ It is likely the improved performance of the gluteal muscles, seen through improved internal hip abduction moments, worked to improve performance in stair climbing. Similar improvements in gait speed occurred in 4 of the 5 participants and in balance ability for all 5 participants. To counter the dynamic nature of fast walking, and to remain stable during static and dynamic balance tasks, efficient hip abductor performance to stabilize the pelvis is required, which was observed in the participants in the NMR program, thus contributing to the improvements in functional performance.

Neuromuscular reeducation techniques have been successfully used in rehabilitation for other chronic injury populations—specifically, after anterior cruciate ligament (ACL) reconstruction and in rehabilitation for patients following ankle sprain.^{27,31,47,48} Emphasizing pelvic stability during functional tasks (e.g., single limb standing, walking, running, and hopping) effectively improves gait mechanics,²⁷ increases hip abductor strength,⁴⁷ increases joint stability,⁴⁸ and prevents further injury.³¹ The findings of this case series support that these techniques may also be successful in a post-THA population, expanding the utility of these training techniques and improving movement quality for these patients.

There are limitations to acknowledge in this case series. We included a small number of participants, with intervention delivered by one treating therapist. It is unknown if the same findings would be present in a larger scale investigation with multiple therapists and more patients. Further, the study design precludes the ability to determine cause and effect; therefore it is unknown whether the intervention directly influenced the observed outcomes. Additionally, this analysis did not include biomechanical outcomes for joints other than the involved hip. The effects of this intervention and changes in movement strategy may be more thoroughly understood by investigating biomechanics in other joints and body segments.

The results of this case series indicate that NMR techniques as part of a postoperative THA rehabilitation program provided a positive effect on biomechanical outcomes, functional performance, and muscle strength. Promoting pelvic stability through focusing on the hip abductor muscles' ability to resist external moments may contribute to improved performance on tasks such as stair climbing, fast walking, and balance. The results suggest that NMR offers a unique effect on movement quality and biomechanical outcomes, which were not seen in the comparison group, despite improved hip abductor strength. Future study is warranted to examine if the addition of NMR to a postoperative THA exercise program has the potential to improve persistent movement compensations.

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Highlights

- Movement compensation during daily activity is common after total hip arthroplasty.
- Five patients completed a post-surgical neuromuscular reeducation exercise program.
- Changes in movement strategy and function following intervention are described.
- Neuromuscular reeducation may improve hip abductor moments during functional tasks.
- Neuromuscular reeducation may improve functional performance after hip arthroplasty.

Figure 1.

Illustrates the changes in the internal hip abduction moment of the surgical limb during level walking for 1 NMR patient and 1 CON participant.

Table 1

Patient Demographics

Group	Patient	Height (m)	Weight (kg)	BMI (kg/m ²)	Age (y)	Sex	Surgical Limb
NMR	2	1.73	127	42.58	50	Male	Left
	6	1.77	104.33	33.3	68	Male	Right
	7	1.63	65.77	24.88	60	Female	Right
	8	1.83	87.54	26.17	54	Male	Right
	9	1.55	68.04	28.36	59	Female	Left
CON	1	1.80	120.2	36.98	64	Male	Right
	3	1.68	84.82	30.12	53	Female	Left
	4	1.57	65.32	26.34	71	Female	Left
	5	1.70	102.6	35.42	57	Female	Left
	10	1.83	101.46	30.34	67	Male	Left

BMI= Body Mass Index

Table 2

Preoperative and Postoperative Hip Kinetics during Level Walking

Group	Patient	Peak Internal Hip Abduction Moment (Nm/kg)		Percent Change*		Peak Vertical Ground Reaction Force (% Body Weight)		Percent Change*	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
NMR	2	-0.132	-0.560	-324.242		1.000	1.216	-21.600	
	6	-0.028	-0.220	-685.714		0.942	1.070	-13.588	
	7	-0.630	-0.640	-1.587		1.038	1.060	-2.119	
	8	-0.468	-0.489	-4.487		1.178	1.160	1.528	
	9	-1.450	-0.358	75.310		1.045	1.240	-18.660	
CON	1	-1.205	-0.402	66.639		1.050	1.016	3.210	
	3	-0.583	-0.568	2.556		1.040	1.004	3.462	
	4	-0.664	-0.530	20.181		1.105	1.085	1.810	
	5	-0.295	-0.243	17.627		1.042	1.025	1.631	
	10	-0.365	-0.370	-1.370		0.998	0.989	0.902	

* Negative percent change values indicate improved values from preoperative to post-intervention values.

Table 3
Preoperative and Postoperative Hip Kinetics during Stepping Up and Landing from a Step

		Peak Internal Hip Abduction Moment (Nm/kg)		Percent Change*	Peak Vertical Ground Reaction Force (% Body Weight)		Percent Change*
Stepping Up Task							
Group	Patient	Pre	Post		Pre	Post	
NMR	2	-0.149	-0.451	-202.68	0.968	0.961	0.72
	6	-0.109	-0.287	-163.30	0.805	0.898	-11.55
	7	-0.387	-0.423	-9.30	1.01	0.92	8.91
	8	-0.269	-0.138	48.70	1.00	1.019	-1.90
	9	NA	-0.237	NA [†]	NA	1.069	NA [†]
CON	1	-0.112	-0.402	-258.93	0.923	0.858	7.04
	3	-0.663	-0.344	48.11	0.913	0.93	-1.86
	4	-0.363	NA	NA	0.664	NA	NA
	5	-0.343	0.917	367.35	1.012	-0.214	121.15
	10	-0.132	-0.088	33.33	0.982	0.959	2.34
Landing Task							
Group	Patient	Pre	Post		Pre	Post	
NMR	2	-0.359	-0.842	-134.54	1.848	2.308	-24.89
	6	-0.027	-0.504	-1766.70	1.178	1.984	-68.42
	7	-0.602	-0.812	-34.88	1.469	1.682	-14.50
	8	-0.585	-0.357	38.97	1.709	1.906	-11.53
	9	NA	-0.341	NA [†]	NA	1.852	NA [†]
CON	1	-0.457	-1.308	-186.21	1.872	1.983	-5.93
	3	-0.933	-0.735	21.22	1.583	1.582	0.06
	4	-0.737	-0.468	36.50	1.113	0.867	22.10
	5	-0.341	-0.518	-51.91	1.386	1.786	-28.86
	10	-0.344	-0.415	-20.64*	1.086	1.191	-9.67

* Negative Percent Change values indicate improved values from preoperative to post-intervention values

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Patient could not perform the task preoperatively but could following the intervention
Patient could not perform the task following the intervention

Table 4

Preoperative and Postoperative Functional Performance and Strength Outcomes.

Group	Patient	Stair Climb Test (seconds)		4-Meter Walk (seconds)		Percent Change *		6-Minute Walk Test (meters)		Percent Change †		Fullerton Advanced Balance Scale (FAB)		Percent Change ‡		Hip Abductor Strength (Nm/kg)		Percent Change §	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
NMR	2	15.82	11.70	-26.04	2.35	2.14	-8.94	484.6	537.1	10.82	26	29	11.54	0.37	0.55	48.65			
	6	11.75	8.55	-27.23	2.42	1.87	-22.73	443.2	560.8	26.55	25	26	4.00	0.71	0.91	28.17			
	7	15.78	13.56	-14.07	3.59	2.67	-25.63	396.2	495.9	25.15	27	29	7.41	0.73	0.89	21.92			
	8	10.05	9.43	-6.17	2.05	2.18	6.34	543.2	649.2	19.53	27	29	7.41	1.17	1.4	19.66			
	9	45.69	25.31	-44.60	4.08	2.73	-33.09	103.6	416.1	301.47	17	28	64.71	0.25	0.38	52.00			
CON	1	22.49	25.30	12.49	3.20	3.27	2.19	303.3	365.8	20.60	28	24	-14.29	0.7	0.34	-51.43			
	3	16.72	13.51	-19.20	2.83	2.49	-12.01	443.8	483.7	9.00	31	26	-16.13	0.84	0.38	-54.76			
	4	14.61	22.40	53.32	3.07	2.93	-4.56	493.8	423.7	-14.20	23	23	0.00	0.63	0.56	-11.11			
	5	21.44	18.81	-12.27	3.32	3.33	0.30	407.8	432.8	6.13	22	20	-9.09	0.4	0.73	82.50			
	10	13.73	14.34	4.44	2.87	3.22	12.20	420.0	509.0	21.19	23	21	-8.70	0.35	0.54	54.29			

* Negative percent change values indicate improvement from preoperative to post-intervention values.

† Positive percent change values indicate improvement from preoperative to post-intervention values.