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Research article

Robot-assisted gait training for limb-girdle muscular dystro-phy: a pathway to improved functional independence

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Abstract: Limb-Girdle Muscular Dystrophy (LGMD) encompasses a group of rare genetic muscle disorders characterized by progressive weakness and wasting of the proximal limb muscles, mainly impacting the proximal limb-girdle musculature. The aim of the study was to assess the effects of complex medical rehabilitation, including robotic exoskeleton training, on muscle strength and functional independence in adult patients with LGMD. This case-series study included 8 patients hospitalized for rehabilitation treatment. They received a personalized training plan that included robot-assisted gait training, which was applied 3 times, at 6 months intervals, each rehabilitation session lasting 12 days. Functional independence was assessed with the Barthel Index and Functional Independence Measure. Baseline measurements were taken at the first admission to the hospital, second assessment after 6 months, and the third assessment after 1 year. Our results revealed that robotic therapy improved muscle strength and motor control, significantly improving hip flexion, bilaterally, in adult LGMD patients. Speed change, body weight support, distance change, and duration change showed important gains in seven out of the eight cases. Robotic-assisted training also improved functional independence, but statistically non-significantly. Based on our results, we consider that robotic devices have potential to be further used in rehabilitation of LGMD patients..

Keywords: limb–girdle muscular dystrophy, medical rehabilitation, robotic exoskeletal devices

1. Introduction

Limb-Girdle Muscular Dystrophy (LGMD) comprises a group of genetic muscle disorders characterized by progressive weakness and wasting of the proximal limb muscles, mainly impacting the proximal limb-girdle musculature. Additionally, muscle contractures, scapular winging, and scoliosis can occur in certain forms of the disease. The onset and progression of LGMD vary widely, with symptoms emerging from early childhood to adulthood and advancing at different rates among individuals [1].

LGMDs result from mutations in approximately 40 genes that encode proteins essential for muscle function and integrity. These mutations disrupt normal muscle physiology, leading to muscle fiber degeneration. The inheritance patterns of LGMDs

are primarily autosomal recessive and autosomal dominant. The specific genetic mutation often correlates with the disease subtype, inheritance pattern, and clinical presentation [2].

The estimated prevalence for all forms of LGMD ranges from 1/44,000 to 1/123,000, but it can vary greatly between countries [3].

LGMDs are progressive disorders, with symmetrical weakness of the proximal muscles. Patients may experience difficulty with rising from a seated position, climbing stairs or lifting objects overhead. As the disease progresses, mobility may become increasingly impaired, potentially leading to reliance on assistive devices or wheelchairs. The diagnosis requires a comprehensive approach that includes a detailed clinical evaluation, family history and a series of diagnostic tests. Elevated serum creatine kinase (CK) levels are commonly found, indicating muscle damage. Electromyography can reveal myopathic changes, while muscle biopsy may show dystrophic features and aid in identifying specific protein deficiencies. Magnetic resonance imaging of muscles can also provide valuable information regarding the pattern and extent of muscle involvement, assisting in differential diagnosis. Genetic testing has significantly enhanced diagnostic accuracy by enabling the identification of specific gene mutations associated with different LGMD subtypes [4-6].

Currently, treatment focuses on managing symptoms and improving quality of life. A multidisciplinary approach is essential, involving physical therapy to maintain muscle strength and flexibility, occupational therapy to assist with daily activities, and respiratory therapy when necessary. Orthopedic interventions may be required to address contractures or scoliosis [7, 8].

Innovative rehabilitation technologies, such as the Lokomat robotic gait training system and wearable exoskeletons, have shown promise in enhancing mobility and functional independence in affected individuals. The Lokomat is a robotic-assisted device that facilitates repetitive, task-specific gait training by guiding the patient's legs on a treadmill, thereby promoting neuroplasticity and muscle re-education [9]. Studies have demonstrated that Lokomat training can improve walking speed, endurance, and overall gait performance in patients with neuromuscular disorders. Initially used in rehabilitation of patients with spinal cord injury and stroke, robotic systems offer precise control and accurate support, guiding patients through correct movement patterns and providing consistent training. They can be programmed and adjusted to match a patient's specific abilities and progress, allowing for tailored and adaptive exercises, and real-time monitoring of a patient's performance [10].

Exoskeleton training, particularly using HAL® (Hybrid Assistive Limb) exoskeletons in conjunction with treadmill therapy, shows promise as a safe and innovative approach to improve walking, balance, and endurance in patients with LGMD. While research specific to LGMD is ongoing, preliminary findings suggest that exoskeleton-assisted therapy can be repeated without adverse effects, leading to beneficial and persistent improvements in functional mobility and enhance the quality of life for patients with muscle weakness although further controlled clinical trials are needed to confirm long-term effects and establish definitive outcomes. ~~may offer functional benefits~~ [10].

The aim of the study was to assess the effects of complex medical rehabilitation, including robotic exoskeleton training, on muscle strength and functional independence in adult patients with LGMD.

2. Materials and Methods

2.1. Study Design and Participants

This case series study was conducted between January 01, 2023 and December 31, 2024, on all patients with muscular dystrophy admitted to the Medical Rehabilitation Clinical Hospital Băile Felix, Romania. Patients were diagnosed through interdisciplinary consultation, based on clinical consultation, paraclinical and laboratory

examinations, as well as genetic tests in some cases. All patients with muscular dystrophies were invited to participate in the study. Inclusion criteria were the following: (1) patients diagnosed with limb-girdle muscular dystrophy; (2) age ≥ 18 years; (3) patients with motor deficit of hip and knee extensor and flexor muscle groups; (4) without respiratory failure. Exclusion criteria were: (1) severe limitations of hip and knee joints range of motion; (2) body weight >100 kg, (3) severe osteoporosis, (4) non-consolidated fractures; (5) severe heart failure; (6) bedsores; (7) cognitive deficit; (8) patients who could not be assessed 3 times. The flow diagram of patients selection is presented in Figure 1.

All patients signed the informed consent and agreed to participate in the study. The study was performed in accordance to the principles of the Declaration of Helsinki and was approved by the Local Ethics Commission for Scientific Research of the Medical Rehabilitation Clinical Hospital Băile Felix, Romania (no 1208716.10.2023).

Patients included in the study were hospitalized 3 times for rehabilitation treatment, at 6-month intervals. They received a personalized training plan that was tailored to meet the specific needs and capabilities of each case. Robotic therapy was performed on all patients.

Baseline measurements were taken at the first admission in the hospital, second assessment session was performed after 6 months and the 3rd assessment after 1 year, following Lokomat therapy.

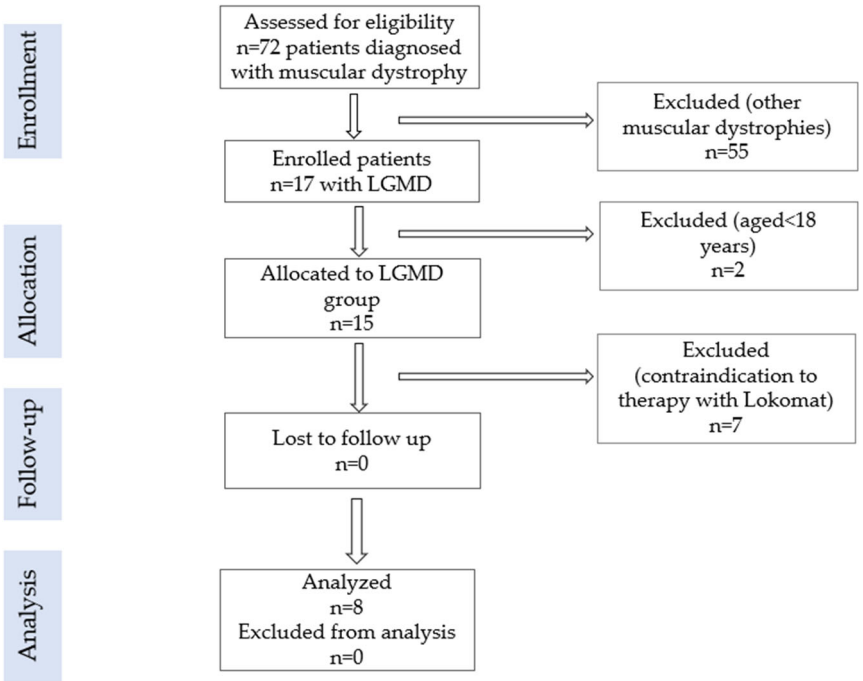

Figure 1. The workflow diagram of patients' selection.

2.2. Assessments

Patient baseline demographic characteristics and comorbidities were collected.

The Cumulative Illness Rating Scale (CIRS), a validated clinical tool to assess and quantify chronic medical conditions, was used. This scale evaluates 14 body systems—including cardiac, vascular, respiratory, gastrointestinal, hepatic, renal, genitourinary, musculoskeletal, neurological, psychiatric, endocrine/metabolic, and sensory—rating each from 0 (no problem) to 4 (life-threatening or end organ failure). The total score (0–56) reflects cumulative comorbidity, and the severity index (average per system) indicates average illness severity [11-13].

Musculoskeletal evaluations—including assessments of active and passive range of motion (ROM), muscle strength in the girdles and limbs, as well as stability

and balance—were conducted both prior to and following the rehabilitation program. ROM was measured using a universal goniometer, with bilateral assessments of the shoulder, hip, and knee joints [14-18].

Muscle strength was evaluated through manual testing based on the Medical Research Council (MRC) scale, which ranges from grade 5 (normal strength) to grade 0 (no muscle contraction). The total muscle strength was represented by the MRC-sum score, calculated as the sum of all individual muscle grades [19-21].

Trunk stability and balance were assessed using specific evaluation tools, with a positive result indicated by the patient leaning to one side.

Assessment of functional abilities, particularly activities of daily living (ADL) were performed using the Barthel Index and Functional Independence Measure (FIM). FIM is a standardized tool widely used in medical rehabilitation. It evaluates a patient's level of functional independence across 18 tasks grouped into two domains—motor (13 items) and cognitive (5 items). Each item is rated on a 7-point scale from 1 (total assistance) to 7 (complete independence), the total score ranging from 18 (complete dependence) to 126 (complete independence). The motor subscale score (the sum of the motor items) (MSS) ranges from 13 to 91. The cognition subscale score (the sum of the cognition items) (CSS) ranges from 5 to 35. [22-24].

The Barthel Index is a validated scale used to assess a person's ability to perform ten basic activities of daily living (ADL), by rating each activity based on the level of assistance required (0 = complete dependence; total possible score = 100). Higher Barthel scores reveal greater independence. A Barthel score of 100 indicates complete independence in performing daily activities [25-30].

The Functional Ambulation Category (FAC) is a simple measurement tool used to classify walking ability. A six-point scale is used specifically focusing on the level of physical support required. It categorizes walking ability from 0 (non-functional) to 5 (independent) [31,32].

Assessments were performed by the same blinded assessor.

2.3. Medical Rehabilitation

The objectives of rehabilitation therapy were: (1) preserve muscle strength and delay functional decline; (2) maintain mobility, prevent contractures, and support independence; (3) improve respiratory capacity and reduce fatigue; (4) enhance quality of life (QoL) and psychological well-being.

The means and approaches used in this study were patient-focused. They include: (1) supervised resistance training; (2) respiratory physiotherapy; (3) range-of-motion (ROM) and flexibility exercises; (4) energy conservation and pacing; (5) occupational therapy; (6) assistive devices and orthoses; (7) technological and multidisciplinary enhancements.

The rehabilitation treatment was individualized, based on muscle strength, joint mobility, balance, coordination, and gait. The rehabilitation treatment was complex and was performed over 3 training sessions every 6 months. Each training session lasted for 12 days. It included combined approaches: exercise therapy, robotic gait training, occupational therapy, and massages.

2.3.1. Exercise Therapy

Exercise sessions were conducted twice daily for 30 minutes each, beginning with muscle stretching and light toning exercises.

Passive limb mobilizations were gently performed within the joint's functional range of motion. These movements aimed to preserve joint flexibility, relax the capsulo-ligamentous structures, stimulate small muscle blood vessels and venous-lymphatic circulation, and help retain the kinesthetic awareness of the involved body segments. Over time, therapy progressed from active-assisted mobilization to fully active movements.

Transfer training was conducted using specific techniques to improve mobility.

To build upper limb strength, isotonic resistance exercises involving active movements were used. For the lower limbs, assisted active movements across the full range of motion were introduced first, followed by manual resistance exercises and isometric contractions to strengthen the pelvic girdle. Progressive resistance strength training was done in both sitting and standing positions, targeting 1–3 muscle groups per session, with 8–12 repetitions per group over a 2-minute period.

Coordination and balance training was supported by assistive devices such as crutches, walking sticks, and walkers, as well as a Bobath ball. Gait retraining included treadmill walking on both flat and inclined surfaces.

2.3.2. Occupational Therapy

The goals of occupational therapy included restoring active mobility, strength, and coordination in both the upper and lower limbs; achieving the highest possible level of functional independence in self-care activities; establishing a healthy balance between rest, work, and leisure; improving performance in activities of daily living (ADLs); and enhancing quality of life by adapting the home environment to the patient's specific abilities. Sessions were conducted twice daily, each lasting 30 minutes. Passive pedaling exercises for the upper and lower limbs were used to enhance sitting balance. Gradual verticalization was introduced cautiously to prevent possible vegetative responses. Attendants were trained in proper techniques for assisting with patient transfers and supporting the patient during ADLs.

2.3.3. Robotic-Assisted Gait Training

Robotic-assisted gait therapy was carried out using the Lokomat®Pro (Hocoma, Switzerland), a device designed to deliver automated, intensive locomotor rehabilitation. The system guides patients through computer-controlled, physiologically accurate walking patterns, while providing dynamic, adjustable body weight support. [33,34].

The Lokomat®Pro features motorized, individually adjustable leg braces that assist walking on a treadmill. It also includes a visual display for real-time feedback and gait performance monitoring. Key training parameters—such as speed, range of motion, weight support, and guidance force—can be tailored to the specific needs of each patient. The assessment tools used were L-FORCE (isometric force of flexion/extension muscle groups in hip and knee joints) and L-ROM (range of motion of flexion/extension in hip and knee joints). The first session's duration was 20 min, progressively increasing the time, reaching 30 minutes daily, and progressively increasing the speed of movement.

2.3.4. Massage

Massage therapy was performed daily, for 20 minutes. With the aim of improving muscle relaxation, reducing muscle soreness, softening tender and trigger points, and for a general sedative effect, the effleurage technique for the cervical, dorsal, and lumbar spine was used. Limb massage was also performed in all cases, using two basic strokes of massage, effleurage and petrissage, intending to improve circulation, reduce edema and facilitate an increase of mobility of the joints and soft tissues [35-37].

The contribution of rehabilitation therapy to regain functional autonomy was assessed using the FIM gain, Barthel Index scores, and LOKOMAT parameters (speed; body weight support; distance change; duration change; L-ROM; L-FORCE). FIM, Barthel index and Lokomat parameters were documented at baseline (the first day of hospital admission), after 6 months and after 1 year (at discharge from the rehabilitation clinic), after completing the rehabilitation programs.

2.4. Statistical Analysis

MedCalc statistical software version 22.005 (MedCalc Software Ltd, Ostend, Belgium) was used to analyse our data. The Kolmogorov–Smirnov test was used to test data for normality. They were presented as mean ± SD. The non-parametric Mann-Whitney test was used to ensure the validity of the results. Paired t-tests were performed to identify the differences between results at first admission in the hospital and discharge after 6 months and 1 year, respectively. A p-value < 0.05 was considered significant.

3. Results

A number of 72 patients were admitted to the Medical Rehabilitation Clinical Hospital Baile Felix, Romania for medical rehabilitation after being diagnosed with different types of muscular dystrophies. Out of all cases, eight patients with LGMD (mean age 42 ± 10.61 years; five males) met the eligibility criteria. Patients' characteristics are presented in Table 1.

Table 1. Patients' characteristics.

Case	Gender	Age (years)	Onset age (years)	Comorbidities	CIRS score
1	M	40	20	Flaccid tetraparesis, predominantly proximal Secondary respiratory failure	7
2	M	37	15	Organic personality disorder Bilateral congenital clubfoot, operated Left radial head fracture, operated	7
3	M	52	12	Restrictive respiratory failure Congestive heart failure NYHA II Hypertension grade I with additional high cardiovascular risk	6
4	M	26	18	Double thoracolumbar scoliosis Lumbar disc herniation	3
5	M	55	44	Cervical polydiscopathy with right disc herniation C5-C6 and paramedian disc herniation C6-C7 Right scapulohumeral periarthritis Chronic painful ischemic cardiopathy Left ventricular failure NYHA II Post-pulmonary thromboembolism status	10
6	F	30	17	Chronic vertebrogenic lumbosacral pain aggravated	2
7	F	51	15	Spina bifida L5-S1 operated with myelodyspasia Chronic vertebrogenic lumbosacral pain Epilepsy Obesity grade I	11
8	F	45	7	Restrictive respiratory failure Post-immobilization osteoporosis Right scapulohumeral periarthritis	5
		Mean ± SD	**Mean ± SD**		**Mean ± SD**
		42±10.61	18.50 ± 11.05		6.38 ± 3.11

CIRS − Cumulative Illness Rating Scale; FAC − Functional Ambulation Categories; SD − standard deviation.

Total FIM score as well as MSS subscore increased with each training session, except for one patient. Barthel score also improved with training, with the same exception. FAC score slightly improved in 5 cases, did not change in 2 cases, and decreased in one case. FIM scores, MSS and CSS subscores, as well as Barthel and FAC scores, are shown in Table 2.

Table 2. FIM and Barthel scores at first admission, after 6 months, and after 1 year.

Case	FIM Score and interpretation			Barthel Score and interpretation			FAC		
	B	6m	1y	B	6m	1y	B	6m	1y
1	60(52.3%) MSS=42 CSS=24 moderate assistance	75(59.5%) MSS=50 CSS=25 moderate assistance	77(61.1%) MSS=52 CSS=25 moderate assistance	40 severe dependence	55 severe dependence	55 severe dependence	1	2	2
2	42(33.3%) MSS=30 CSS=12 maximal assistance	49(38.8%) MSS=37 CSS=12 maximal assistance	54(42.8%) MSS=44 CSS=10 maximal assistance	40 severe dependence	45 severe dependence	50 severe dependence	1	2	2
3	98(77.7%) MSS=76 CSS=22 minimal assistance	110(87.3%) MSS=80 CSS=30 minimal assistance	115(91.2%) MSS=85 CSS=30 minimal assistance	60 severe dependence	70 moderate dependence	75 moderate dependence	3	4	4
4	98(77.7%) MSS=78 CSS= 20 minimal assistance	98(77.7) MSS=78 CSS= 20 minimal assistance	110(87.3%) MSS=90 CSS=20 minimal assistance	50 severe dependence	55 severe dependence	60 severe dependence	1	1	1
5	53 (42%) MSS=33 CSS=20 maximal assistance	65(51.5%) MSS=42 CSS=23 moderate assistance	70(55.5%) MSS=46 CSS=24 moderate assistance	55 severe dependence	60 severe dependence	70 moderate dependence	2	3	3
6	79(62.7%) moderate assistance MSS=55 CSS=24	74(58.7%) moderate assistance MSS=50 CSS=24	55(43.7%) severe assistance MSS=31 CSS=24	45 severe dependence	45 severe dependence	35 severe dependence	2	2	1
7	53 (42%) MSS=45 CSS=24 maximal assistance	63(50%) MSS=50 CSS=24 moderate assistance	64(50.7%) MSS=51 CSS=24 moderate assistance	45 severe dependence	50 severe dependence	55 severe dependence	0	0	0
8	90(71.4%) MSS=70 CSS= 20 moderate assistance	95(75.4) MSS=75 CSS= 20 minimal assistance	98(77.7%) MSS=78 CSS=20 minimal assistance	50 severe dependence	60 severe dependence	60 severe dependence	**1**	**1**	**1**

FIM − Functional Independence Measure; MSS − Motor subtotal score; CSS − Cognitive subtotal score; FAC − functional ambulation category; B – Baseline; 6m − After 6 months; 1y −After 1 year.

Comparison of FIM total score, MSS and CSS subscores, and Barthel scores over specified timepoints showed that they did not reach a statistically significant change in 6-months'/1 year time (Table 3).

Table 3. FIM and Barthel scores mean values and statistical significance (p).

Mean FIM score ± SD			p	Mean Barthel score ± SD			p
B	**6m**	**1 y**		**B**	**6m**	**1 y**	
71.62± 20.88	78.62±19.26	80.37±22.67	0.69/0.43	48.12±6.58	55±7.90	57.5±11.45	0.07/ 0.06
MSS	**MSS**	**MSS**					
53.62± 17.88	57.75± 16.05	59.62±20.26	0.48/0.62				
CSS	**CSS**	**CSS**					
20.75±3.73	22.25±4.86	22.12±5.44	0.69/0.58				

FIM − Functional Independence Measure; SD − standard deviation; p-value: between the first and second evaluation / first and last evaluation; MSS − Motor subtotal score; CSS − Cognitive subtotal score.

The functional outcome measures: lower-limb range of motion (L-ROM) and lower force (L-FORCE) for hip and knee flexion and extension, before and after robotic-assisted therapy via Lokomat are shown in tables 4 and 6. Statistically significant differences were noted for right hip flexion and for left hip flexion (Tables 5, 7).

Table 4. Lokomat assessment: L-ROM.

L-ROM (°)	**Case 1**			**Case 2**			**Case 3**			**Case 4**		
Parameter	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**
Hip flexion right	17	24	59	27	30	51	30	36	46	30	36	46
Hip flexion left	24	46	64	24	35	46	40	44	47	40	42	47
Hip extension right	5	8	10	10	12	14	5	10	14	5	10	14
Hip extension left	6	10	12	10	12	13	0	5	7	0	5	7
Knee flexion right	75	75	78	55	55	60	27	36	52	27	36	52
Knee flexion left	79	80	80	65	68	75	25	42	50	25	36	50
Knee extension right	**10**	10	10	5	5	5	6	10	10	6	8	12
Knee extension left	**9**	10	10	5	5	5	7	7	9	7	8	9
	Case 5			**Case 6**			**Case 7**			**Case 8**		
Parameter	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**
Hip flexion right	17	42	59	9	8	5	27	46	51	31	36	42
Hip flexion left	24	42	64	9	8	5	24	46	46	16	22	28
Hip extension right	5	5	10	5	0	0	10	10	14	12	10	12
Hip extension left	6	6	12	6	0	0	10	10	13	5	5	5
Knee flexion right	75	75	78	45	24	17	55	55	60	53	59	75
Knee flexion left	79	79	80	49	20	16	65	70	75	36	38	42
Knee extension right	10	10	10	10	0	0	5	5	5	5	5	5
Knee extension left	9	9	10	9	0	0	5	5	5	5	5	5

B − baseline; 6m − 6 months; 1y − 1 year.

Two measures show statistically significant increases over time, indicating an improvement in function or mobility. The other measures show no significant differences, indicating either stability or that the changes are not large enough to be considered significant (Table 5).

Table 5. Means and standard deviations for L-ROM.

L-ROM (°)	Mean ± SD/B	Mean ± SD/6m	Mean ± SD/1y	p value
Hip flexion right	23.5± 7.58	32.25±11.11	44.88±16.1	0.0043
Hip flexion left	25.13±9.94	35.63±12.83	43.38±18.03	0.0251
Hip extension right	7.13±2.8	8.13±3.62	11±4.47	0.0569
Hip extension left	5.38±3.57	6.63±3.6	8.63±4.39	0.119
Knee flexion right	51.5±17.23	51.88±17.4	59±18.85	0.4201
Knee flexion left	52.88±20.95	54.13±21.31	58.5±21.48	0.6046
Knee extension right	7.13±2.26	6.63±3.31	7.13±3.76	1
Knee extension left	7±1.73	6.13±2.93	6.63±3.28	0.7819

Table 6. Lokomat assessment: L FORCE.

L FORCE (Nm/degree)	Case 1			Case 2			Case 3			Case 4		
Parameter	**B**	**6m**	**1 y**	**B**	**6m**	**1y**	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**
Hip flexion right	26	28	32	29	30	30	28	31	31	48	50	61
Hip flexion left	26	28	32	29	30	30	18	28	29	18	24	59
Hip extension right	28	28	34	28	28	29	28	29	29	28	37	49
Hip extension left	28	30	34	28	28	29	22	23	28	32	49	58
Knee flexion right	13	18	21	18	20	22	23	25	28	43	43	48
Knee flexion left	13	18	21	18	20	22	23	25	27	43	43	47
Knee extension right	9	15	18	19	19	19	25	39	39	25	32	39
Knee extension left	9	15	18	19	19	19	24	32	49	24	35	49
	Case 5			**Case 6**			**Case 7**			**Case 8**		
Parameter	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**	**B**	**6m**	**1 y**
Hip flexion right	46	51	65	9	2.7	2.7	29	32	40	46	48	52
Hip flexion left	46	55	65	9	3.5	0.8	29	35	40	47	48	50
Hip extension right	28	32	44	5	3.2	3	28	32	39	48	48	48
Hip extension left	28	32	44	6	4	0	28	29	39	54	54	54
Knee flexion right	13	25	31	3	1.3	0.8	18	25	32	46	48	48
Knee flexion left	13	25	31	3	1.7	1.2	18	25	32	50	50	50
Knee extension right	9	25	28	5	2.8	1.7	19	25	29	44	45	45
Knee extension left	9	18	28	9	3	1.6	19	24	29	46	45	46

B − baseline; 6m − 6 months; 1y − 1 year.

Table 7. Means and standard deviations for L-FORCE

L FORCE Nm/degree	Mean±SD/B	Mean±SD/6m	Mean±SD/1y	p value
Hip flexion right	32.63±12.47	34.09±14.94	39.21±18.85	**0.0043**
Hip flexion left	27.75±,12.51	31.44±14.59	38.23±18.98	**0.0251**
Hip extension right	27.63±10.77	29.65±11.76	34.38±13.95	0.0569
Hip extension left	28.25±12.31	31.13±14.41	35.75±16.93	0.119
Knee flexion right	22.13±14.02	25.66±13.63	28.85±14.34	0.4201
Knee flexion left	22.63±14.91	25.96±13.96	28.9±14.44	0.6046
Knee extension right	19.38±11.68	25.35±12.61	27.34±13.23	1
Knee extension left	19.88±11.58	23.88±12.29	29.95±16.03	0.7819

SD − standard deviation.

Analysis of Lokomat parameters demonstrated an improvement of the analyzed parameters in 87.5% of cases (Table 8).

Table 8. Lokomat assessment: changes between first and last assessment

Case	1	2	3	4	5	6	7	8	APC
Speed Change (km/h)	+46%	+158%	+ 52%	+ 50%	+49%	+1%	+148%	+30%	+66.75%
Body weight support (kg)	+ 48%	+ 47%	+ 17%	+ 20%	+ 46%	-1%	+ 42%	+33%	+31.50%
Distance Change (meters)	+144 %	+ 381%	+195%	+ 180%	+204 %	-19%	+ 285%	+ 76%	+180.75%
Duration Change (min)	+216 %	+ 99%	+ 99%	+ 89%	+146 %	-20 %	+ 82%	+39%	+93.75%

APC- average percentage change.

3. Discussion

The aim of the study was to assess functionality and independence of patients with LGMD after medical rehabilitation using robotic exoskeletal devices. The results of the present study revealed that exoskeleton robotic training, which was applied 3 times, at 6 months interval, each rehabilitation session lasting 12 days, was significantly effective in improving hip flexion bilaterally in adult LGMD patients. Speed change, body weight support, distance change and duration change showed important gains in seven out of the eight cases.

Limb girdle muscular dystrophies are a group of rare genetic disorders characterized by atrophy and weakness of the striated muscles of the hip and shoulder (limb-girdle areas). The muscle weakness and atrophy are progressive and may also affect other muscles. This group of diseases is an excellent example of heterogeneous disorders, primarily affecting the proximal muscles of the girdles. There are more than 30 different subtypes, which have been associated with specific genetic abnormalities. Depending on the inheritance pattern, they can be classified as autosomal dominant (type 1) or recessive (type 2). Dominant forms are less common (<10% of all cases) and generally present with less severe phenotypes and onset during adulthood. Recessive forms are more common (1:15,000), with type 2A being the most common (OMIM #253600) [38]. The onset age of the latter subtype is variable, ranging from 8 to 15 years, although later onset forms have also been described [39]. The onset age, severity and progression of the different disease subtypes can vary greatly not only between unrelated affected individuals, but even among individuals in the same family. Some individuals may have a mild, slowly progressive form of the disorder, while others may have a rapidly progressive form that causes severe disability [40].

Disease-specific therapy, aiming to cure the disease, is not yet available; therefore, therapies include different symptomatic treatments. Other potential therapies like molecular or gene therapy approaches are under investigation [2]. Due to the broad heterogeneity of this group of disorders, there is no single approach. Medical rehabilitation is beneficial for maintaining or ameliorating strength and improving quality of life. Muscle training exercises must be carefully managed and tailored to patient's needs. This will help patients maintain their daily living activities as the disease progresses, having also a positive impact on their psychological well-being [7,10,41,42].

In our study the main objective of rehabilitation therapy was to preserve or increase muscle strength. Though the evolution of LGMDs is progressive, tailored resistance and endurance training can enhance muscular capacity and slow deterioration. Also, physiotherapy targeted joint range-of-motion and daily function to delay loss of mobility.

We carefully evaluated each case, combined rehabilitation methods and personalized each patient's therapeutic plan. Frequency of exercise training, duration and intensity can vary significantly. Rehabilitative treatment plays a key role in prevention of, and compensation for, loss of muscle strength and therefore in preserving for

as long as possible the patient's maximum autonomy. The disease makes it difficult for patients to sustain prolonged muscular effort and frequently causes fatigue, which occurs when the intended physical activity can no longer be continued or is perceived as excessive effort and discomfort. It is, therefore, necessary to balance muscle training, which improves strength and quality of life of patients, with the need to preserve the delicate muscle fibers that can easily be damaged with the wrong type of exercise [43,44].

The use of robotics in medical rehabilitation has been recommended as an alternative to reduce the burden on therapists. Exoskeletons were initially used for rehabilitation of neurological conditions, less extensively for musculoskeletal disorders [45,46]. These robotic devices, such as the Lokomat, have developed into robot-assisted gait trainers—fixed grounded robotics paired with a treadmill and body weight support system that aid forward lower limb movement—offering functional training benefits and increased session intensity, though they remain limited to forward stepping and only hospital use [9,46-48].

In our study, FIM and Barthel scores improved after medical rehabilitation, except one case. When comparing the functional abilities scores from admission with those obtained after the 6-month rehabilitation session, and after the 1-year rehabilitation session, respectively, we noticed improving scores, but differences were not statistically significant, which is likely attributed to the small number of cases and the progression of the disease.

Seven patients included in the present study improved the total FIM score and the motor section of FIM. Functional independence improvement was notable in 2 cases that initially required maximal assistance, subsequently requiring moderate assistance after medical rehabilitation. One patient reported improved independence, from moderate assistance to minimal assistance. We noticed that gains in FIM motor scores were significantly higher than cognitive subscale scores.

The results suggest that ROM and strength measurements are more sensitive for detecting functional changes at the local level, whereas the FIM score, being a global measure of independence, may require more extensive change. Therefore, even if patients show significant increases in hip ROM and strength, these changes do not necessarily directly influence the global independence score, at least within the observation period.

Sczesny-Kaiser et al. performed a treadmill exercise study using hybrid assistive limb (HAL®). Safety and effects on walking function of HAL® supported treadmill therapy was assessed in 3 patients with LGMD, who received 8 weeks of treadmill training with HAL®, 3 times a week. All patients completed the therapy and reported improvements in endurance and in the measured outcome parameters, improved functional ability in weak patients and enhanced lower limb strength and walking distance. The authors concluded that HAL® treadmill training enabled an intensive highly repetitive locomotor training, beneficial for patients [10]. Regarding the motor section of FIM, Sczesny-Kaiser M et al. found that motor scores of two patients increased after HAL® therapy, whereas one patient did not exhibit any change [10].

Barthel scores also showed a slight improvement in our study. A change from severe dependence to moderate dependence on the Barthel Index was achieved in two cases. A PubMed search using the following key words: limb girdle muscular dystrophy, medical rehabilitation, Barthel index combined with robotic device or Lokomat or exoskeleton, did not give any result, therefore we could not compare our results to other studies.

Loss of ADL independence and immobility leads to a sedentary lifestyle that promotes the occurrence of secondary diseases. In our study CIRS score was higher in patients with a longer period of disease progression. Therefore, gait recovery is an important goal of medical rehabilitation.

Some subtypes of LGMD may involve cardiac and respiratory muscles, necessitating attentive monitoring for cardiomyopathy and respiratory failure. We also

aimed to improve respiratory capacity in patients 1, 3 and 8, who had respiratory failure. The evolution of these 3 patients was favorable, FIM and Barthel scores improving in all of them. Integrating breathing exercises alongside motor training supports endurance and respiratory function. Our programs combined deep breathing, intercostal stretching, and pursed-lip breathing, which were effective in improving thoracic expansion and reducing dyspnea. Early management of respiratory symptoms and personalized respiratory physiotherapy contributes to patients' well-being and improves their capacity to participate in muscle training exercises [44].

Supervised resistance training over months showed improvements in muscle strength and endurance with good tolerability. In our study statistically significant muscle strength gains were recorded for right hip flexion and for left hip flexion. Improvements were also observed for the other muscle groups, but were not statistically significant. In patient 2 muscle strength values remained the same, even after the last training session. In case 6, we noticed an increase in muscle strength at the 6-month' evaluation, but marked reduction in muscle strength was observed after 1 year, when performing the third assessment. Increased knee flexion strength and improvements in functional tasks in adults with muscular dystrophy were reported after a twice-a-week, 12 weeks, resistance training programme. The authors noticed a significant improvement in knee flexion, but no significant change in knee extension [49].

Analyzing changes between the first and last assessment in Lokomat parameters, the following aspects were notable: speed change revealed an increase around 50% in 4 cases (patients 1, 3, 4, 5), and noticeable values in other 2 patients (158% in case 2 and 148% in case number 7, respectively). There was an augmentation of body weight support of over 40% in cases 1, 2, 5 and 7. Except for patient 6, the other cases had an increase ranging from 17% to 33%. Regarding walking distance, the smallest increase, 76%, was seen in patient 8 and a notable 381% difference between initial and final values in patient 2. Patient 6 had a 19% reduction of the walking distance. Duration change also revealed important improvements in the majority of cases, except for the same patient 6. Patient 6's decline is notable, reflecting disease progression, in our opinion. She participated in all the training sessions, was compliant, but had unfavorable evolution. She is scheduled for a muscle biopsy. Our results are in agreement with the results of the only study dealing with robotic training of patients with LGMD, when noting the improvement of functional abilities, but also when discussing about patients that had a downward trend [10].

The Lokomat promotes gait patterns centered on hip movements, leading to an increase [50]. The LOKOMAT system assists hip and knee flexion/extension movements, as well as pelvic rotation, with hip and knee movements being controlled by an impedance controller. Visual feedback may contribute to increased results [51]. Therefore, the more pronounced improvement in hip flexion during Lokomat therapy can be explained by the emphasis on hip-related gait patterns, as well as the technology and algorithms used to stimulate and correct this specific movement.

Only one case from the present study, a young woman, had an unfavorable evolution, all the assessments revealing worsening of the measured parameters, with the exception of a minor improvement in speed (1%). A study by Brun et al. showed that teenagers with higher self-reported physical activity level before the onset of symptoms had an increased risk for early onset of symptoms and wheelchair use and an increase in the disease progression rate [52].

The discrepancy between objective (L-ROM/L-FORCE) and subjective/functional (FIM/Barthel) outcomes can be explained by the difference in the assessment method and perspectives used. Objective outcomes, such as L-ROM and L-FORCE, are based on direct and quantifiable measurements made by professionals, providing an accurate picture of the patient's physical capabilities. On the other hand, subjective

or functional outcomes, such as FIM and Barthel, are evaluated according to the patient's perception and performance in daily activities, which can be influenced by factors such as motivation, personal adaptation, or the level of social support. Thus, differences may arise due to the fact that the patient may have a different perception of his/her real ability to perform certain activities compared to the objective measurements. Also, certain physiological or psychological aspects may influence the subjective results, leading to a lack of perfect correlation between the two types of assessments. In conclusion, this difference emphasizes the importance of using a multidisciplinary and complementary approach to fully assess the patient's status, combining objective measurements with subjective assessment to obtain the most complete and accurate possible picture.

Our observations indicate that, in most cases, FAC scores showed minimal change between assessments. Some scales, including FAC, may have limited sensitivity to detect subtle variations depending on the stage of recovery or severity of the condition. Ceiling and floor effects: If patients started with scores very close to the upper (ceiling) or lower (floor) limit of the FAC scale, the ability to detect significant improvement or deterioration is limited. This phenomenon may mask real changes in patients' functioning. In such cases, minimal differences may actually be the result of methodological limitations, not a lack of real change.

There is an ongoing debate regarding neuromuscular functional rehabilitation, the benefits and risks of exercise training for patients with muscular dystrophies. Strength training and aerobic training are considered safe and potentially beneficial in the rehabilitation of these patients. Analyzing safety and long-term effect of exercise on disease progression and use of assisted exercise such as body weight-supported physiotherapy approaches and anti-gravity training in patients with LGMD, several studies concluded that exercise is generally safe and well tolerated, and improves functional outcomes in patients with hereditary muscle disorders, but exercise prescriptions should be disease specific [53-55].

Investigating the effect of strength training in patients with LGMD, Sveen et al. concluded that low-intensity and high-intensity training increased muscle strength and endurance in some of the muscles that were tested, suggesting that supervised resistance training could be adviced in the management of these patients [56].

A review of the currently available motor rehabilitation strategies for the most common subtypes of LGMD concluded that, when tailored to individual needs, muscle training can enhance strength and functional abilities, positively impacting psychological well-being [44].

Emerging methods such as virtual reality (VR) and robotics show promise for engaging motor training in the future, though specific LGMD trials are limited today. The studies investigating the use of VR for muscular dystrophy rehabilitation showed improvements in the motor abilities and independence in these patients [57]. On the other hand, non-grounded exoskeletons that combine the advantages of grounded robotics with the ability to practice all aspects of walking can assist a person's standing and walking [46,58].

Strengths and limitations of the study

The study provided valuable insights by highlighting the benefits of exoskeleton-assisted robotic rehabilitation for adult patients with LGMD, demonstrating significant improvements in hip flexion; It also attempts to fill a gap in the literature by emphasizing the feasibility and tolerability of personalized and repeated therapy, which opens new perspectives for the development and implementation of effective therapeutic interventions in muscular dystrophies. Of course, we also point out some limitations. The most important limitation of the study is the low number of cases, as

LGMD is a rare disease. Another limitation of our study is that we only used patient parameters over a period of one year. Also, the lack of control group makes it hard to separate the effects of robotics treatment from general rehabilitation. Furthermore, the use of this robot technology is still limited, as these devices are large and heavy, requiring supervision and the use of walking aids. In addition, evidence supporting their benefits is still limited to short-intervention trials with few participants [58].

5. Conclusions

We have presented a case-series of eight patients with LGMD, who underwent a personalized, comprehensive, multidisciplinary rehabilitation therapy. Robotic gait-assisted therapy was performed in all cases and it improved or maintained muscle strength, motor control and functional autonomy. Exoskeleton rehabilitation was effective in significantly improving hip flexion range of motion, bilaterally. Based on our results, we consider that robotic devices have potential to be further used in rehabilitation of LGMD patients.

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References

1. Mercuri, E.; Bönnemann, C.G.; Muntoni, F. Muscular dystrophies. Lancet 2019, 394, 2025–2038. https://doi.org/10.1016/S0140-6736(19)32910-1
2. Bouchard, C.; Tremblay, J.P. Limb-Girdle Muscular Dystrophies Classification and Therapies. J. Clin. Med. 2023, 12, 4769. https://doi.org/10.3390/jcm12144769
3. Liu, W.; Pajusalu, S.; Lake, N.J.; et al. Estimating prevalence for limb-girdle muscular dystrophy based on public sequencing databases. Genet. Med. 2019, 21, 2512–2520. https://doi.org/10.1038/s41436-019-0544-8
4. Carter, J.C.; Sheehan, D.W.; Prochoroff, A.; Birnkrant, D.J. Muscular Dystrophies. Clin. Chest Med. 2018, 39, 377–389. https://doi.org/10.1016/j.ccm.2018.01.004
5. LaPelusa, A.; Asuncion, R.M.D.; Kentris, M. Muscular Dystrophy. In: StatPearls [Internet]; StatPearls Publishing: Treasure Island, FL, USA, 2025. PMID: 32809417
6. von der Hagen, M.; Schallner, J.; Kaindl, A.M.; et al. Facing the genetic heterogeneity in neuromuscular disorders: Linkage analysis as an economic diagnostic approach towards the molecular diagnosis. Neuromuscul. Disord. 2006, 16, 4–13. https://doi.org/10.1016/j.nmd.2005.10.001
7. Siciliano, G.; Simoncini, C.; Giannotti, S.; Zampa, V.; Angelini, C.; Ricci, G. Muscle exercise in limb girdle muscular dystrophies: Pitfall and advantages. Acta Myol. 2015, 34, 3–8. PMID: 26155063
8. Trofin, D.; Matei, D.; Stamate, T.; Walther, B.; Trofin, D.M. Rehabilitation Challenges in Limb-Girdle Muscular Dystrophies. Balneo PRM Res. J. 2021, 12, 31–33. https://doi.org/10.12680/balneo.2021.415
9. Gassert, R.; Dietz, V. Rehabilitation robots for the treatment of sensorimotor deficits: A neurophysiological perspective. J. Neuroeng. Rehabil. 2018, 15, 46. https://doi.org/10.1186/s12984-018-0383-x

10. Sczesny-Kaiser, M.; Kowalewski, R.; Schildhauer, T.A.; et al. Treadmill Training with HAL Exoskeleton—A Novel Approach for Symptomatic Therapy in Patients with Limb-Girdle Muscular Dystrophy—Preliminary Study. Front. Neurosci. 2017, 11, 449. https://doi.org/10.3389/fnins.2017.00449
11. Napolitani, M.; Kundisova, L.; Messina, G.; Nante, N. The applicability of methods for assessing comorbidities: The Cumulative Illness Rating Scale (CIRS). Eur. J. Public Health 2019, 29 (Suppl_4), ckz187.089. https://doi.org/10.1093/eurpub/ckz187.089
12. Hudon, C.; Fortin, M.; Vanasse, A. Cumulative Illness Rating Scale was a reliable and valid index in a family practice context. J. Clin. Epidemiol. 2005, 58, 603–608. https://doi.org/10.1016/j.jclinepi.2004.10.017
13. Di Raimondo, D.; Pirera, E.; Pintus, C.; et al. The Role of the Cumulative Illness Rating Scale (CIRS) in Estimating the Impact of Comorbidities on Chronic Obstructive Pulmonary Disease (COPD) Outcomes: A Pilot Study of the MACH (Multidimensional Approach for COPD and High Complexity) Study. J. Pers. Med. 2023, 13, 1674. https://doi.org/10.3390/jpm13121674
14. Barker, K.D.D.; Johnson, M.M. The Physiatric History and Physical Examination. In Braddom's Physical Medicine and Rehabilitation, 6th ed.; Cifu, D.X., Ed.; Elsevier: Philadelphia, PA, USA, 2021; pp. 1–41.e2. ISBN 978-0-323-62539-5
15. Hancock, G.E.; Hepworth, T.; Wembridge, K. Accuracy and reliability of knee goniometry methods. J. Exp. Orthop. 2018, 5, 46. https://doi.org/10.1186/s40634-018-0161-5
16. Mullaney, M.J.; McHugh, M.P.; Johnson, C.P.; Tyler, T.F. Reliability of shoulder range of motion comparing a goniometer to a digital level. Physiother. Theory Pract. 2010, 26, 327–333. https://doi.org/10.3109/09593980903094230
17. Nussbaumer, S.; Leunig, M.; Glatthorn, J.F.; et al. Validity and test-retest reliability of manual goniometers for measuring passive hip range of motion in femoroacetabular impingement patients. BMC Musculoskelet. Disord. 2010, 11, 194. https://doi.org/10.1186/1471-2474-11-194
18. Cejudo, A.; Sainz de Baranda, P.; Ayala, F.; De Ste Croix, M.; Santonja-Medina, F. Assessment of the Range of Movement of the Lower Limb in Sport: Advantages of the ROM-SPORT I Battery. Int. J. Environ. Res. Public Health 2020, 17, 7606. https://doi.org/10.3390/ijerph17207606
19. Compston, A. Aids to the Investigation of Peripheral Nerve Injuries. Brain 2010, 133, 2838–2844. doi: 10.1093/brain/awq270. PMID: 20928945.
20. Paternostro-Sluga, T.; Grim-Stieger, M.; Posch, M.; et al. Reliability and Validity of the Medical Research Council (MRC) Scale and a Modified Scale for Testing Muscle Strength in Patients with Radial Palsy. J. Rehabil. Med. 2008, 40, 665–671. https://doi.org/10.2340/16501977-0223
21. Vanhoutte, E.K.; Faber, C.G.; van Nes, S.I.; Jacobs, B.C.; van Doorn, P.A.; van Koningsveld, R.; Cornblath, D.R.; van der Kooi, A.J.; Cats, E.A.; van den Berg, L.H.; et al. Modifying the Medical Research Council Grading System through Rasch Analyses. Brain 2012, 135, 1639–1649. https://doi.org/10.1093/brain/aws084
22. Dodds, T.A.; Martin, D.P.; Stolov, W.C.; Deyo, R.A. A validation of the functional independence measurement and its performance among rehabilitation inpatients. Arch. Phys. Med. Rehabil. 1993, 74, 531–536. https://doi.org/10.1016/0003-9993(93)90119-u
23. Kidd, D.; Stewart, G.; Baldry, J.; Johnson, J.; Rossiter, D.; Petruckevitch, A.; Thompson, A.J. The Functional Independence Measure: A comparative validity and reliability study. Disabil. Rehabil. 1995, 17, 10–14. https://doi.org/10.3109/09638289509166622
24. Voll, R.; Krumm, B.; Schweisthal, B. Functional Independence Measure (FIM) assessing outcome in medical rehabilitation of neurologically ill adolescents. Int. J. Rehabil. Res. 2001, 24, 123–131. https://doi.org/10.1097/00004356-200106000-00005
25. Ohura, T.; Hase, K.; Nakajima, Y.; Nakayama, T. Validity and reliability of a performance evaluation tool based on the modified Barthel Index for stroke patients. BMC Med. Res. Methodol. 2017, 17, 131. https://doi.org/10.1186/s12874-017-0409-2
26. Collin, C.; Wade, D.T.; Davies, S.; Horne, V. The Barthel ADL Index: A reliability study. Int. Disabil. Stud. 1988, 10, 61–63. https://doi.org/10.3109/09638288809164103
27. Stone, S.P.; Ali, B.; Auberleek, I.; Thompsell, A.; Young, A. The Barthel Index in clinical practice: Use on a rehabilitation ward for elderly people. J. R. Coll. Physicians Lond. 1994, 28, 419–423. PMID: 7807430; PMCID: PMC5401036.
28. Mayoral, A.P.; Ibarz, E.; Gracia, L.; Mateo, J.; Herrera, A. The use of Barthel Index for the assessment of the functional recovery after osteoporotic hip fracture: One year follow-up. PLoS ONE 2019, 14, e0212000. https://doi.org/10.1371/journal.pone.0212000
29. Green, J.; Forster, A.; Young, J. A test–retest reliability study of the Barthel Index, the Rivermead Mobility Index, the Nottingham Extended Activities of Daily Living Scale and the Frenchay Activities Index in stroke patients. Disabil. Rehabil. 2001, 23, 670–676. https://doi.org/10.1080/09638280110045382
30. Bouwstra, H.; Smit, E.B.; Wattel, E.M.; van der Wouden, J.C.; Hertogh, C.M.P.M.; Terluin, B.; Terwee, C.B. Measurement properties of the Barthel Index in geriatric rehabilitation. J. Am. Med. Dir. Assoc. 2019, 20, 420–425.e1. https://doi.org/10.1016/j.jamda.2018.09.033

31. Mehrholz, J.; Wagner, K.; Rutte, K.; Meiner, D.; Pohl, M. Predictive validity and responsiveness of the Functional Ambulation Category in hemiparetic patients after stroke. Arch. Phys. Med. Rehabil. 2007, 88, 1314–1319.
32. Schindl, M.R.; Forstner, C.; Kern, H.; Hesse, S. Treadmill training with partial body weight support in nonambulatory patients with cerebral palsy. Arch. Phys. Med. Rehabil. 2000, 81, 301–306.
33. Gorgey, A.S. Robotic exoskeletons: The current pros and cons. World J. Orthop. 2018, 9, 112–119. https://doi.org/10.5312/wjo.v9.i9.112
34. Cevei, M.; Onofrei, R.R.; Gherle, A.; Gug, C.; Stoicanescu, D. Rehabilitation of post-COVID-19 musculoskeletal sequelae in geriatric patients: A case series study. Int. J. Environ. Res. Public Health 2022, 19, 15350. https://doi.org/10.3390/ijerph192215350
35. Field, T. Massage therapy research review. Complement. Ther. Clin. Pract. 2016, 24, 19–31. https://doi.org/10.1016/j.ctcp.2016.04.005
36. Crawford, C.; Boyd, C.; Paat, C.F.; Price, A.; Xenakis, L.; Yang, E.; Zhang, W. The Impact of Massage Therapy on Function in Pain Populations—A Systematic Review and Meta-Analysis of Randomized Controlled Trials: Part I, Patients Experiencing Pain in the General Population. Pain Med. 2016, 17, 1353–1375.
37. Furlan, A.D.; Giraldo, M.; Baskwill, A.; Irvin, E.; Imamura, M. Massage for low-back pain. Cochrane Database Syst. Rev. 2015, 2015, CD001929. https://doi.org/10.1002/14651858.CD001929.pub3
38. OMIM. Available online: https://omim.org/entry/253600 (accessed on 25 July 2025).
39. Wang, C.H.; Liang, W.C.; Minami, N.; Nishino, I.; Jong, Y.J. Limb-girdle muscular dystrophy type 2a with mutation in CAPN3: The first report in Taiwan. Pediatr. Neonatol. 2015, 56, 62–65. https://doi.org/10.1016/j.pedneo.2013.01.018
40. Angelini, C. LGMD. Identification, description and classification. Acta Myol. 2020, 39, 207–217. https://doi.org/10.36185/2532-1900-024
41. O'Dowd, D.N.; Bostock, E.L.; Smith, D.; Morse, C.I.; Orme, P.; Payton, C.J. The effects of 12 weeks' resistance training on psychological parameters and quality of life in adults with Facioscapulohumeral, Becker, and Limb-girdle dystrophies. Disabil. Rehabil. 2022, 44, 5950–5956. https://doi.org/10.1080/09638288.2021.1955306
42. Vissing, C.R.; Preisler, N.; Husu, E.; Prahm, K.P.; Vissing, J. Aerobic training in patients with anoctamin 5 myopathy and hyperckemia. Muscle Nerve 2014, 50, 119–123. https://doi.org/10.1002/mus.24112
43. D'Este, G.; Spagna, M.; Federico, S.; Cacciante, L.; Cieślik, B.; Kiper, P.; Barresi, R. Limb-girdle muscular dystrophies: A scoping review and overview of currently available rehabilitation strategies. Muscle Nerve 2025, 71, 138–146. https://doi.org/10.1002/mus.28284
44. Lovering, R.M.; Porter, N.C.; Bloch, R.J. The muscular dystrophies: From genes to therapies. Phys. Ther. 2005, 85, 1372–1388.
45. Grimmer, M.; Riener, R.; Walsh, C.J.; et al. Mobility related physical and functional losses due to aging and disease – a motivation for lower limb exoskeletons. J. Neuroeng. Rehabil. 2019, 16, 2. https://doi.org/10.1186/s12984-018-0458-8
46. Abery, P.; Canetti, F.D.; Hing, W. The role of lower limb exoskeletons in rehabilitation: A scoping review. Phys. Ther. Rev. 2025, 30, 118–136. https://doi.org/10.1080/10833196.2025.2465937
47. Ilies, A.B.; Cheregi, C.; Thowayeb, H.H.; Wendt, J.R.; Horgos, M.S.; Lazar, L. Lokomat-assisted robotic rehabilitation in spinal cord injury: A biomechanical and machine learning evaluation of functional symmetry and predictive factors. Bioengineering 2025, 12, 752. https://doi.org/10.3390/bioengineering12070752
48. Fritz, H.; Patzer, D.; Galen, S.S. Robotic exoskeletons for reengaging in everyday activities: Promises, pitfalls, and opportunities. Disabil. Rehabil. 2019, 41, 560–563. https://doi.org/10.1080/09638288.2017.1398786
49. Bostock, E.L.; O'Dowd, D.N.; Payton, C.J.; Smith, D.; Orme, P.; Edwards, B.T.; Morse, C.I. The effects of resistance exercise training on strength and functional tasks in adults with Limb-Girdle, Becker, and Facioscapulohumeral dystrophies. Front. Neurol. 2019, 10, 1216. https://doi.org/10.3389/fneur.2019.01216
50. Aurich-Schuler, T., & Labruyère, R. (2019). An Increase in Kinematic Freedom in the Lokomat Is Related to the Ability to Elicit a Physiological Muscle Activity Pattern: A Secondary Data Analysis Investigating Differences Between Guidance Force, Path Control, and FreeD. Frontiers in robotics and AI, 6, 109. https://doi.org/10.3389/frobt.2019.00109
51. Patarini, F., Tamburella, F., Pichiorri, F., Mohebban, S., Bigioni, A., Ranieri, A., Di Tommaso, F., Tagliamonte, N. L., Serratore, G., Lorusso, M., Ciaramidaro, A., Cincotti, F., Scivoletto, G., Mattia, D., & Toppi, J. (2024). On the role of visual feedback and physiotherapist-patient interaction in robot-assisted gait training: an eye-tracking and HD-EEG study. Journal of neuroengineering and rehabilitation, 21(1), 211. https://doi.org/10.1186/s12984-024-01504-9
52. Brun, B.N.; Mockler, S.R.; Laubscher, K.M.; Stephan, C.M.; Collison, J.A.; Zimmerman, M.B.; Mathews, K.D. Childhood activity on progression in Limb Girdle Muscular Dystrophy 2I. J. Child Neurol. 2017, 32, 204–209. https://doi.org/10.1177/0883073816677680
53. Preisler, N.; Orngreen, M.C. Exercise in muscle disorders: What is our current state? Curr. Opin. Neurol. 2018, 31, 610–617. https://doi.org/10.1097/WCO.0000000000000597
54. Sheikh, A.M.; Vissing, J. Exercise therapy for muscle and lower motor neuron diseases. Acta Myol. 2019, 38, 215–232. PMID: 31970320; PMCID: PMC6955630

55. Nandanwar, S.P.; Udhoji, S.P.; Raghuveer, R. Management of a 25-Year-Old Female Patient with Limb-Girdle Muscular Dystrophy with Physiotherapy: A Case Report. Cureus 2024, 16, e51428. https://doi.org/10.7759/cureus.51428
56. Sveen, M.L.; Andersen, S.P.; Ingelsrud, L.H.; Blichter, S.; Olsen, N.E.; Jønck, S.; Krag, T.O.; Vissing, J. Resistance training in patients with Limb-Girdle and Becker muscular dystrophies. Muscle Nerve 2013, 47, 163–169. https://doi.org/10.1002/mus.23491
57. Kiper, P.; Federico, S.; Szczepańska-Gieracha, J.; Szary, P.; Wrzeciono, A.; Mazurek, J.; Luque-Moreno, C.; Kiper, A.; Spagna, M.; Barresi, R.; et al. A Systematic Review on the Application of Virtual Reality for Muscular Dystrophy Rehabilitation: Motor Learning Benefits. Life 2024, 14, 790. https://doi.org/10.3390/life14070790
58. Rodríguez-Fernández, A., Lobo-Prat, J. & Font-Llagunes, J.M. Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. J NeuroEngineering Rehabil 18, 22 (2021). https://doi.org/10.1186/s12984-021-00815-5.