Innovations Health Devices 2026

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White Paper

Force Solution Space

BIOMECHANIGG
SPORT & HEALTH RESEARCH

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A white paper for Innovations Health Devices to establish lower-limb single-plane joint peak force values for the development of the Kinoped.

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Introduction

Peak force is a biomechanical measure derived from a maximal voluntary contraction and is widely used to quantify muscle strength across clinical, sports science, and engineering applications (Jaric, 2002). In clinical settings, maximal strength assessments enable the quantification of muscle weakness, monitoring of neuromuscular disease progression, and support the development of targeted treatment strategies (Meldrum et al., 2007). In sport and performance contexts, these measures are used to evaluate training adaptations and assess strength capabilities in elite and competitive athletes (Warneke et al., 2023). More broadly, maximal force data are also incorporated into musculoskeletal and biomechanical models to inform system-level simulations and engineering design processes (Miehling, 2019).

Within engineering applications, accurate characterization of human force production is essential for the development of wearable robotic systems and exoskeletons designed to augment or replicate human movement. Peak force represents a key design parameter, as it defines the upper limits of human output that robotic systems must accommodate to ensure compatible and effective human–machine interaction (Escarabajal et al., 2026). Normative strength values are therefore required to parameterize biomechanical models that link human force production to robotic actuation, enabling appropriate scaling of assistance across different movement directions and tasks (Escarabajal et al., 2026). In addition, force and torque measurements derived from human movement are commonly used to define actuator requirements and control strategies, ensuring that exoskeleton systems can meet the mechanical demands of functional activities while delivering appropriate levels of assistance or augmentation (Huysamen et al., 2020).

Despite extensive investigation of human strength characteristics, available maximal force data remain fragmented and inconsistently reported across the literature. Many studies focus on isolated muscle groups or single joint actions, limiting the ability to construct a comprehensive representation of whole-limb force production capacity. This lack of standardized and integrative datasets constrains both comparative analysis and translation into engineering applications. In the context of lower-limb exoskeleton design, insufficient representation of true human force-generating capacity may result in poorly calibrated assistance profiles, potentially reducing movement efficiency and user comfort (Huysamen et al., 2020). Accordingly, a unified normative strength database is required to support accurate modeling, device design, and control optimization.

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The objective of this literature review is to develop a consolidated normative database of maximal force values organized according to the primary degrees of freedom of the lower-limb joints. This dataset is intended to support biomechanical modeling and facilitate the design and optimization of lower-limb assistive technologies, including robotic exoskeletons. The review is restricted to healthy adult populations with no history of musculoskeletal injury or surgical intervention, thereby establishing representative normative strength ranges for this population.

Methods

From February 6 to March 18, 2026, a structured literature review was conducted to identify studies reporting peak isometric force values at the lower-limb joints in healthy adults. Seven degrees of freedom across the hip, knee, and ankle joints were analyzed (Table 1). Relevant studies published between March 1, 1991, and August 31, 2025, were retrieved from two electronic databases: SPORTDiscus and PubMed.

All studies were in the English language. For both databases, the following search terms were used: (hip OR knee OR ankle OR lower limb) AND (flexion OR extension OR abduction OR adduction OR internal rotation OR external rotation OR eversion OR inversion OR dorsiflexion OR plantarflexion) AND (peak torque OR MVC OR maximal voluntary contraction OR isometric) AND (normative or reference) NOT (children OR adolescents OR youth OR child OR teenage) NOT (replacement OR injury OR trauma OR surgery).

Studies reporting peak force values in populations with musculoskeletal injuries, prior surgery, or trauma were excluded, as were studies reporting only on children. Eligible studies for this review were required to report isometric peak force movements. No restrictions were placed on the assessment protocol, sex, or physical activity levels of the sample population to capture a broad range of normative peak force values across the healthy adult population.

All scientific articles retrieved by the search strategy underwent a three-stage screening process: title review, abstract review, and full-text review. Articles with relevant titles advanced to abstract review, and studies with contextually relevant abstracts underwent full-text evaluation. Studies that successfully met all inclusion criteria and completed all three screening stages were included in this literature review.

One reviewer evaluated all scientific papers for this literature review. All scientific articles that successfully passed the full-text review had the following data extracted from each paper:

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1. Bibliographic information (lead author, date published, title, journal)
2. Study design (sample size, methods, outcome variables, joint type, movement type)
3. Population characteristics (age, gender, ethnicity, limb dominance)
4. Results (mean, standard deviation)

A weighted average was used to calculate the mean and standard deviation for each degree of freedom, where each sample size was multiplied by its corresponding mean peak force value (Equation 1) or mean standard deviation (Equation 2) and the sum of these products were divided by the total sample size, *n*. The minimum and maximum values were directly reported by each study. The smallest minimum and largest maximum value reported across all studies were used for the absolute minimum and maximum values for each degree of freedom (Table 1).

$$x_w = \frac{\sum_{i=1}^{k} n_i x_i}{\sum_{i=1}^{k} n_i}$$

Equation 1

$$s_w = \frac{\sum_{i=1}^{k} n_i s_i}{\sum_{i=1}^{k} n_i}$$

Equation 2

Table 1 Lower limb joint measurements across seven planes of motion.

Measurement	Joint	Plane	Movement(s)
1	Hip	Sagittal	Flexion Extension
2	Hip	Frontal	Abduction Adduction
3	Hip	Transverse	Internal Rotation External Rotation
4	Knee	Sagittal	Flexion Extension
5	Ankle	Sagittal	Plantarflexion Dorsiflexion
6	Ankle	Frontal	Inversion Eversion
7	Ankle	Transverse	Abduction Adduction

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All peak force values from eligible studies were compiled into a database, categorized by study name, joint (hip, knee, or ankle), movement (flexion, extension, abduction, adduction, internal rotation, external rotation, dorsiflexion, plantarflexion, inversion, eversion) and where stated, age range or gender of the sample. The database was organized by each degree of freedom, as shown in Table 1.

For this review, “sufficient literature” was defined as more than 1500 data points with representation across both sexes and various ages. Each data point had a unique combination of joint, movement plane, and age range. When studies reported additional demographic information such as race or information on which limb was reported (e.g., dominant or non-dominant), this information was also incorporated, creating additional unique combinations. The number of participants in each plane of motion and limb combination ranged from 6 to 1000, depending on each study’s reported sample size.

Results

This literature review search generated 263 results across two databases. The full data reduction process is outlined in Figure 1. All 263 papers underwent title screening, with 135 papers advancing to the abstract review. Of these, 51 proceeded to full-text review, with full-text evaluation identifying 17 papers that explicitly reported on peak isometric force values for inclusion.

Seventeen papers reported peak isometric force values, published between 1991 and 2025 (Table 2). The total pooled sample size across all studies was N = 4085 participants, of whom 48% male (N = 1949) and 52% female (N = 2136). Peak force was most commonly measured with a hand-held dynamometer, used alone in 11 studies (Andrews et al., 1996; Bäckman et al., 2013; Douma et al., 2014; Heijboer et al., 2024; Martín-Miguel et al., 2025; Oliveira et al., 2018; Paris & Sullivan, 1992; Pasco et al., 2020; Phillips et al., 2000; Van Der Ploeg et al., 1991; Vannatta & Kernozek, 2021). One study measured peak force values using only a fixed dynamometer alone (Hoglund et al., 2014), and one study measured these values using both a hand-held dynamometer and a fixed dynamometer (McKay et al., 2017). The remaining studies singularly used individual instruments: a fixed tensiometer (The National Isometric Muscle Strength (NIMS) Database Consortium, 1996), a ForceFrame system (Sandler et al., 2025), and a hand-held pull gauge (Stoll et al., 2000). For each study, the positions of the subject and measurement device were also summarized (Table 3).

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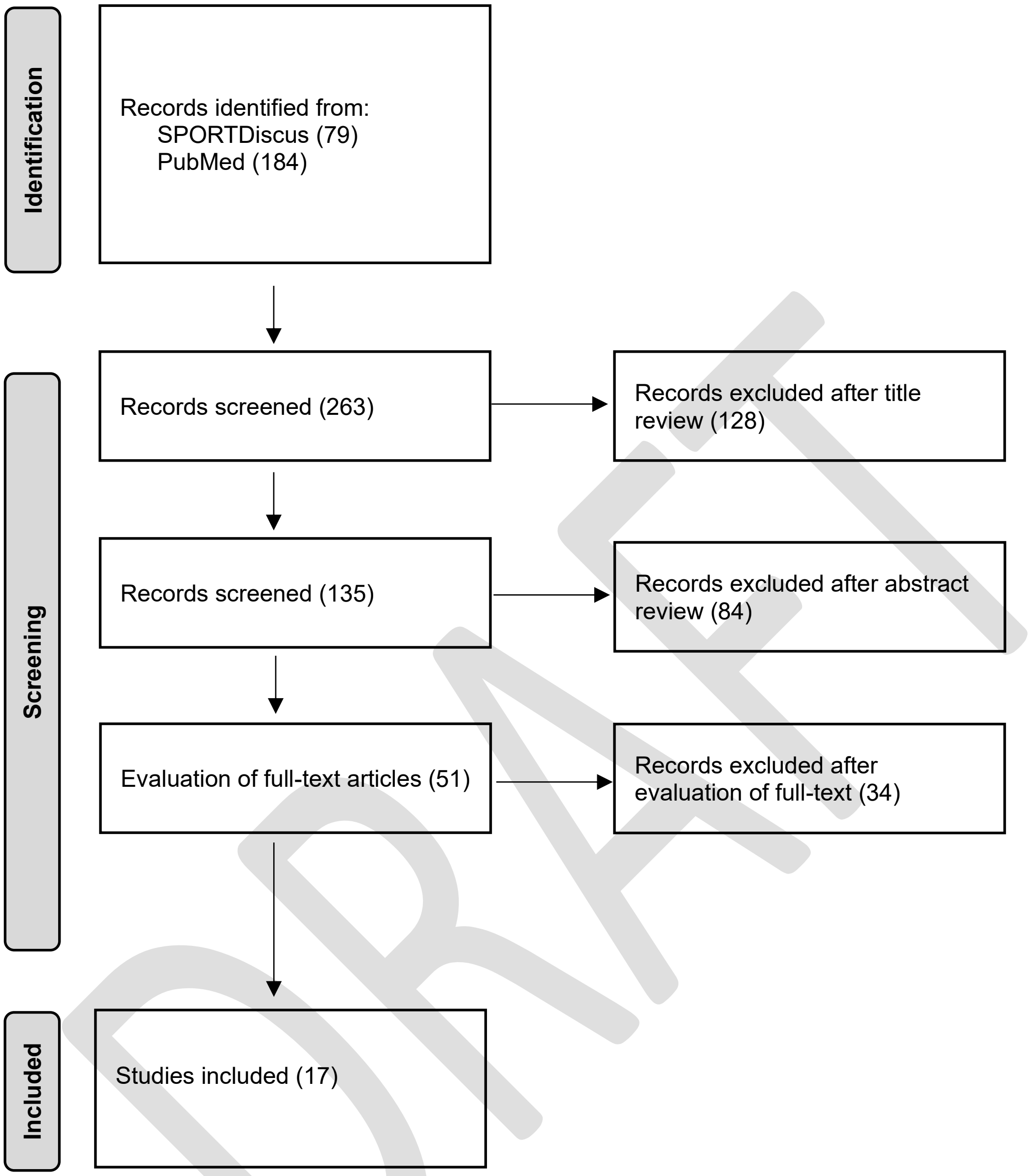

Figure 1 Flowchart of the literature review selection process

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Table 2 Study Demographic Information

Study	Sample size	Joint	Movement	Sex	Age
Andrews, 1996	147	Hip	Flexion, Abduction	Male: 77 Female: 70	50-79
		Knee	Flexion, Extension		
		Ankle	Dorsiflexion		
Bäckman, 2013	128	Hip	Flexion, Abduction	Male:65 Female: 63	20-70
		Knee	Flexion, Extension		
		Ankle	Dorsiflexion		
Bohannan, 1997	231	Hip	Flexion, Abduction	Male: 106 Female: 125	20-79
		Knee	Extension		
		Ankle	Dorsiflexion		
Douma, 2014	462	Knee	Flexion, Extension	Male: 259 Female: 203	20-60
Heijboer, 2024	152	Hip	Adduction, Abduction	Male: 0 Female: 152	18-20
Hoglund, 2014	80	Hip	Internal Rotation, External Rotation	Male: 40 Female: 40	18-28
Martín-Miguel, 2025	297	Hip	Flexion, Extension, Abduction, Adduction, External Rotation, Internal Rotation	Male: 142 Female: 155	16-31
		Knee	Flexion, Extension		
		Ankle	Dorsiflexion, Plantarflexion		
McKay, 2017	700	Hip	Abduction, Internal Rotation, External Rotation	Male: 350 Female: 350	20-101
		Knee	Flexion, Extension		
		Ankle	Dorsiflexion, Plantarflexion		
NIMS, 1996	493	Hip	Flexion, Extension	Male: 220 Female: 273	18-80
		Knee	Flexion, Extension		
		Ankle	Dorsiflexion		
Oliveira, 2017	152	Hip	Flexion, Extension, Abductors	Male: 79 Female: 73	18-65
Paris & Sullivan, 1992	36	Ankle	Inversion, Eversion	Male: 36 Female: 0	18-30
Pasco, 2020	237	Hip	Flexion, Abduction	Male: 89 Female: 148	20-39
Phillips, 2000	200	Hip	Flexion, Abduction	Male: 100 Female: 100	20-69
		Ankle	Dorsiflexion		
Sandler, 2024	45	Hip	Adduction, Abduction, Internal Rotation, External Rotation	Male: 45 Female: 0	24.4 ± 4.07
Stoll, 2000	543	Hip	Flexion, Extension, Abduction, Adduction, External Rotation, Internal Rotation	Male: 253 Female: 290	20-80
		Knee	Flexion, Extension		
		Ankle	Dorsiflexion, Plantarflexion		
Van der Ploeg, 1991	100	Hip	Flexion, Abduction	Male: 50 Female: 50	20-60
		Knee	Extension, Flexion		
		Ankle	Dorsiflexion, Plantarflexion		
Vannatta & Kernozek, 2021	82	Hip	Abduction, External Rotation	Male: 38 Female: 44	18-22

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Table 3 Subject Position and Measurement Tool Placement

Study	Subject Position During Measurement	Tool Placement	Measurement Tool
Andrews, 1996	Hip flexed 90° with knee relaxed, both lower limbs in neutral	At femoral condyles, at lateral femoral condyles	Hand-held dynamometer
	Hips and knees flexed 90° with hands resting in lap	Proximal to malleoli	
	Hip, knee, and ankle at 0°	Proximal to metatarsophalangeal joints	
Bäckman, 2013	Supine at 90°, Supine 30°	Anterior aspect of distal third of thigh, lateral aspect of distal third of thigh	Hand-held dynamometer
	Prone 90°, Sitting 0°	Posterior aspect of distal third of thigh above ankle, anterior aspect of lower leg above the malleoli	
	Sitting 0°	Dorsal aspect of foot above the metatarsophalangeal joint	
Bohannan, 1997	Hip flexed 90° with knee flexed and contralateral hip neutral, both hips neutral with knees extended	Proximal to femoral condyles, proximal to lateral joint line of knee	Hand-held dynamometer
	Hip and knee flexed 90°	Proximal to malleoli	
	Hip and knee fully extended, ankle neutral	Proximal to metatarsophalangeal joints	
Douma, 2014	Hip and knee flexed 90°	Proximal to calcaneous, proximal to talis	Hand-held dynamometer
Heijboer, 2024	Tested leg straight, non-tested leg with hip and knee flexed 90°	8cm proximal to most prominent point of lateral malleolus	Hand-held dynamometer
Hoglund, 2014	Prone with hip at 0° flexion and knee 90°	Opposite anterior knee in line with longitudinal axis of femur	Fixed dynamometer
Martín-Miguel, 2025	Hip and knee flexed 90°, Hip and knee flexed 0° , Hip flexed 0° and knees extended, hip flexed 0° and knee flexed 90°, hip and knee flexed 90°, hip and knee flexed 90°,	Attached to ankle by a strap	Hand-held dynamometer
	Prone with hip extended and knee flexed 90°, prone with knee flexed 0°		
	Supine	Attached to metatarsals	
McKay, 2017	Not reported	Not reported	Hand-held dynamometer
	Not reported	Not reported	Fixed dynamometer
	Not reported	Not reported, long sitting heel over plinth edge	
NIMS, 1996	Trunk supported at 20°, hip at 20°, knee at 90°	Proximal to knee	Fixed strain-gauge tensiometer
	Sitting, hip and knee at 90°	Around malleolus	
	Supine, ankle in plantarflexion	Around metatarasals	
Oliveira, 2017	Supine, Prone with knee flexed at 90°	Distal posterior thigh region, superior to lateral malleolus	Hand-held dynamometer
Paris & Sullivan, 1992	Hip and knee flexed 90° with foot in plantar-dorsiflexion neutral	Distal to medial malleolus	Hand-held dynamometer
Pasco, 2020	Seated with feet hanging above floor level, lying on side with test leg raised 20cm above bench	5cm proximal to patella, 10cm proximal to lateral malleolus	Hand-held dynamometer
Phillips, 2000	Hip and knee flexed 90°, hip abducted 20° with knee extended	Proximal to upper border of patella, proximal to lateral femoral condyle	Hand-held dynamometer
	Hip abducted 10° with knee extended and foot flat on ground	Center of top of foot	
Sandler, 2024	Supine position with hips and knees flexed 0°	4 sensors inside inner and outer panels	ForceFrame system
Stoll, 2000	Predetermined for each muscle group to minimize gravitational force, specific positions not reported	Band at predefined anatomical sites	Hand-held pull gauge
Van der Ploeg, 1991	Supine position with hips and knees flexed 90°, Supine hip flexed 45° and knee flexed 90°	Anterior surface of distal thigh, lateral epicondyle of knee	Hand-held dynamometer
	Prone with knee flexed 45°, prone with knee flexed 90°	Anterior surface of distal shant proximal to ankle joint, heel	
	Supine with foot 90° dorsiflexed	Proximal to metatarsophalangeal joints	
Vannatta & Kernozek, 2021	Supine position with hip flexed 0° and knee fully flexed, prone with knee flexed to 90°	Above the lateral malleolus, above the medial malleolus	Hand-held dynamometer

DRAFT

Across all 17 studies, there were 4085 participants (Table 2). However, because the majority of studies reported on the dominant and non-dominant limb, individual participants often contributed to more than one measurement. Additionally, most studies reported values across at least two out of three of the relevant lower-limb joints (hip, knee, or ankle), resulting in a total of 29724 data points. The distribution of these data points is summarized in Table 4.

Table 4 Number of data points for each plane of movement across the lower-limb joints.

Joint	Movement	Data Points
Hip	Flexion	3815
	Extension	2376
	Abduction	1894
	Adduction	1590
	Internal Rotation	2688
	External Rotation	2852
Knee	Flexion	3908
	Extension	3344
Ankle	Plantarflexion	2560
	Dorsiflexion	4624
	Inversion	36
	Eversion	37
	Abduction*	-
	Adduction*	-

* No data points exist for this movement

The peak force measurements (mean, standard deviation, minimum, and maximum) from each study were compiled into a database and organized by each joint and movement combination outlined in Table 1. This database was used to calculate the pooled mean and standard deviation, as well as the absolute minimum and maximum values for each movement outlined (Table 5). Using the consolidated data from Table 5, plots were created in MATLAB to visualize the distribution of data across each movement plane (Figures 2-6). Due to insufficient literature found

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for ankle inversion, eversion, abduction, and adduction, no figures were created for ankle frontal and transverse plane movements.

Table 5 Weighted average peak force values summarized from scientific literature (N).

Joint	Movement	Minimum	Maximum	Mean	SD
Hip	Flexion	82.0	538.6	299.46	82.45
	Extension	238.4	777.9	458.35	148.04
	Abduction	147.1	513.0	231.57	48.98
	Adduction	122.0	301.2	206.08	58.34
	Internal Rotation	76.5	217.7	133.08	43.04
	External Rotation	76.3	169.4	115.70	33.75
Knee	Flexion	119.0	588.0	237.52	58.94
	Extension	224.9	522.9	370.57	108.05
Ankle	Plantarflexion	216.3	719.1	417.10	127.48
	Dorsiflexion	131.5	491.0	228.66	58.64
	Inversion	-	-	74.73	21.09
	Eversion	-	-	75.22	20.99
	Abduction*	-	-	-	-
	Adduction*	-	-	-	-

* No data points exist for this movement

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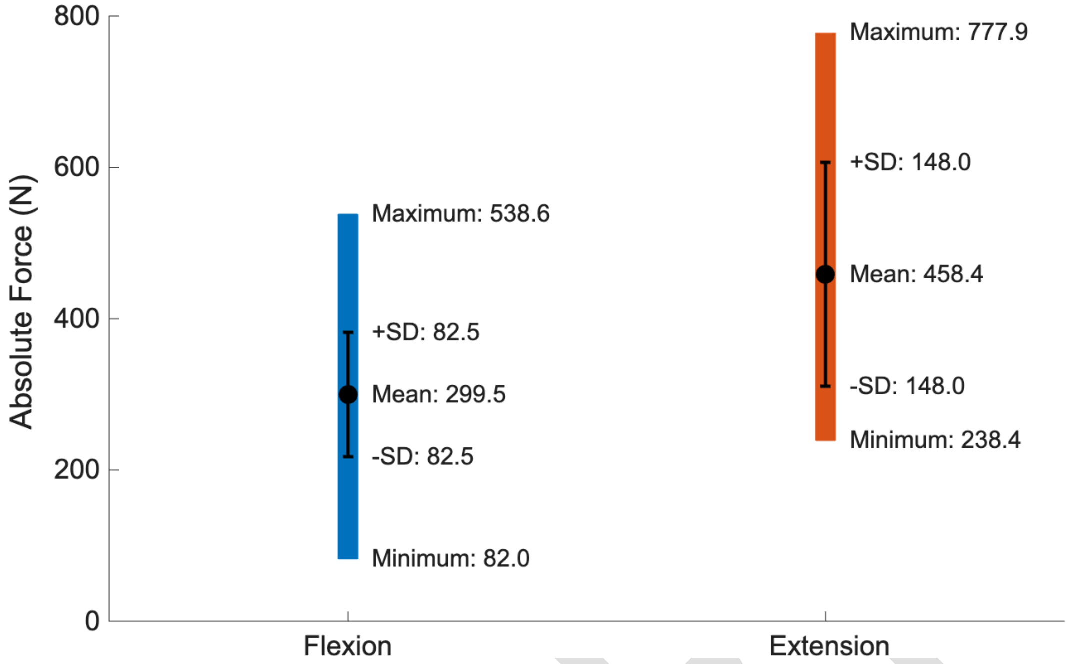

Figure 2 Hip flexion and extension absolute peak force summary. The mean values are represented by black circles, error bars represent ±1 standard deviation, and the colour bars represent the full observed range (minimum to maximum values).

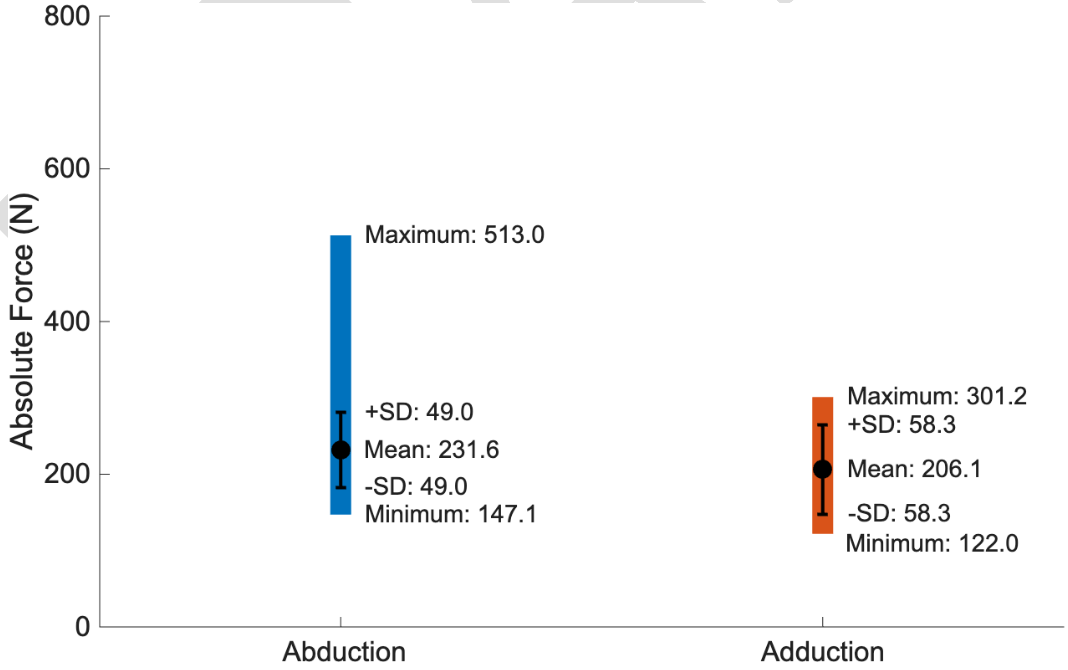

Figure 3 Hip abduction and adduction absolute peak force summary. The mean values are represented by black circles, error bars represent ±1 standard deviation, and the colour bars represent the full observed range (minimum to maximum values).

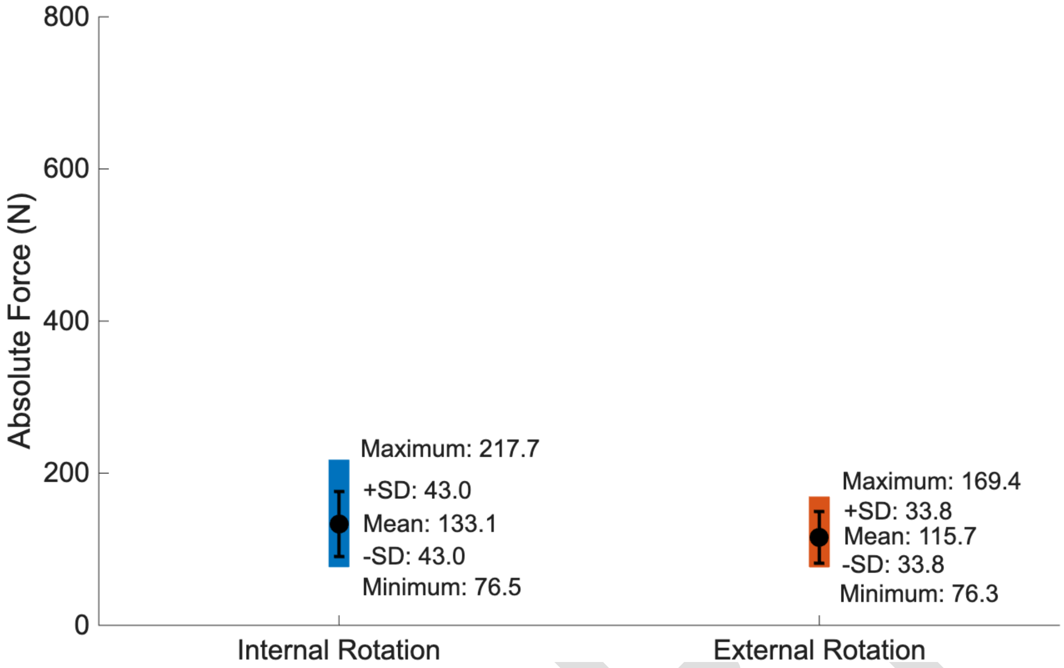

Figure 4 Hip internal and external rotation absolute peak force summary. The mean values are represented by black circles, error bars represent ±1 standard deviation, and the colour bars represent the full observed range (minimum to maximum values).

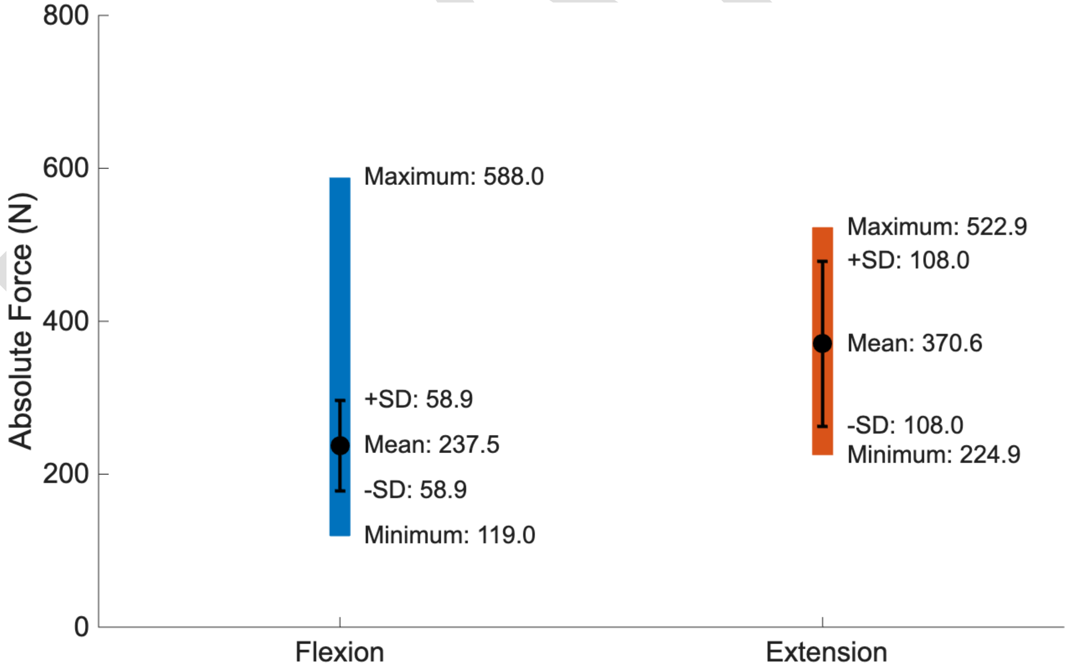

Figure 5 Knee flexion and extension absolute peak force summary. The mean values are represented by black circles, error bars represent ±1 standard deviation, and the colour bars represent the full observed range (minimum to maximum values).

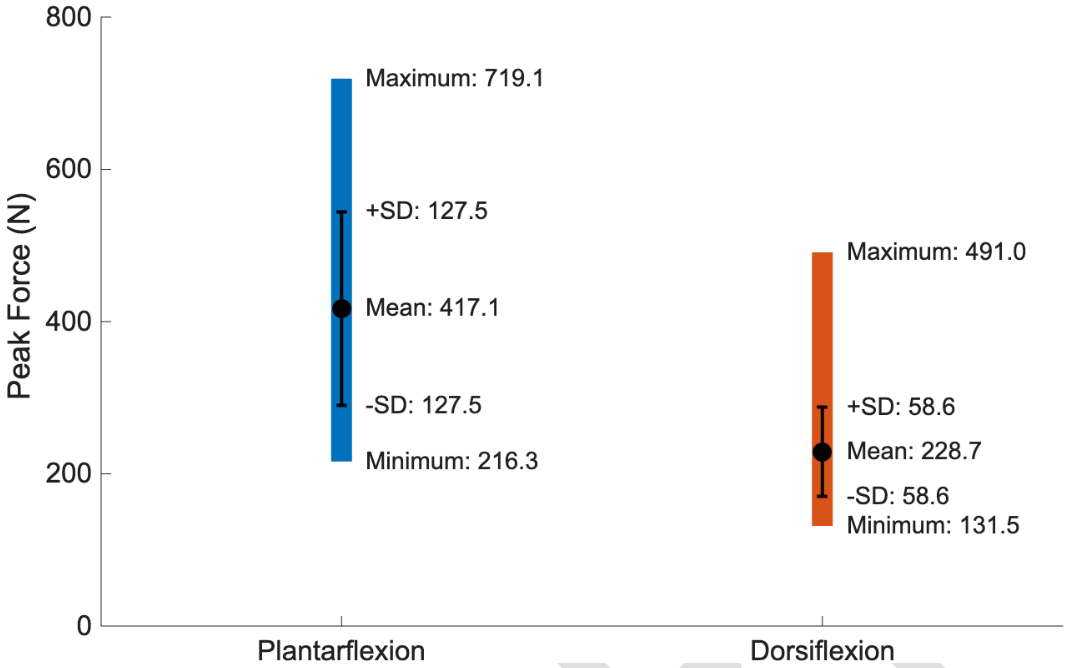

Figure 6 Ankle plantarflexion and dorsiflexion absolute peak force summary. The mean values are represented by black circles, error bars represent ±1 standard deviation, and the colour bars represent the full observed range (minimum to maximum values).

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Discussion

The purpose of this literature review was to develop a solution space for single-plane lower-limb peak isometric force values at the hip, knee, and ankle joints. Of 263 records screened, 17 studies were included, representing a total sample size of 4,085 participants (Table 2). The resulting dataset spans seven degrees of freedom across the lower limb: three at the hip, one at the knee, and three at the ankle (Table 1).

Across the consolidated literature, peak force magnitudes varied systematically by joint and plane of motion. The highest forces were consistently observed in sagittal-plane movements, particularly hip extension (458.35 ± 148.04 N) and knee extension (370.57 ± 108.05 N). Hip and knee extension forces exceeded their respective flexion counterparts (hip flexion: 299.46 ± 82.45 N; knee flexion: 237.52 ± 58.94 N), reflecting the dominant role of the extensor musculature in propulsion during gait (Eng & Winter, 1995). At the ankle, plantarflexion produced substantially higher forces (417.10 ± 127.48 N) than dorsiflexion (228.66 ± 58.64 N), consistent with the larger physiological cross-sectional area and force capacity of the plantarflexor muscle group (Fukunaga et al., 1992). Frontal-plane hip forces were moderate in magnitude (abduction: 231.57 ± 48.98 N; adduction: 206.08 ± 58.34 N), while transverse-plane hip rotations were comparatively lower (internal rotation: 133.08 ± 43.04 N; external rotation: 115.70 ± 33.75 N). Only one study reported frontal-plane ankle forces, with similar magnitudes for inversion and eversion (~75 N), highlighting limited available evidence in this domain.

Considerable inter-individual variability was observed across all joint and movement categories, with wide ranges and standard deviations reflecting heterogeneity in the underlying populations (Table 5). This was most pronounced at the hip, where flexion and extension exhibited broad ranges (hip flexion: 82.0–538.6 N; hip extension: 238.4–777.9 N) and large standard deviations (82.45 N and 148.04 N, respectively). Similar dispersion was observed at the knee and ankle (knee extension SD: 108.05 N; ankle plantarflexion SD: 127.48 N). This variability is expected given the inclusion of functionally diverse cohorts, ranging from older adults with reduced neuromuscular capacity to trained individuals exhibiting strength adaptations due to long-term training exposure (Izquierdo et al., 2002; Hunter et al., 2016). As a result, the aggregated dataset likely reflects a broad functional envelope rather than a single homogeneous population, which limits the interpretability of mean values as representative central estimates.

To address this, percentile-based solution spaces were estimated; however, due to the large variance and reliance on summary statistics, these estimates sometimes extended beyond the reported empirical minimum and maximum values. This highlights a limitation of deriving distributional characteristics from aggregated literature data and suggests that the resulting values should be interpreted as design-oriented approximations rather than strict population percentiles.

From an engineering perspective, the observed force magnitudes provide direct input parameters for lower-limb exoskeleton design, particularly in defining actuator capacity, structural safety margins, and control authority. The highest demand occurs in sagittal-plane hip and knee extension, indicating that actuation systems must be optimized to sustain substantial propulsive loads (Gomez et al., 2017). Multiplanar hip forces further emphasize the need for exoskeleton architectures capable of accommodating coupled loading across flexion–extension, abduction–adduction, and rotational degrees of freedom to preserve physiological movement patterns (Xu et al., 2025). These force profiles are also commonly used to estimate joint torques, which in turn inform actuator selection, structural design constraints, and power system requirements in wearable robotic systems (Greve & Kreischer, 2024; Yandell et al., 2020).

A notable gap in the literature is the underrepresentation of non-sagittal ankle loading. Only inversion and eversion forces were reported in a single study (Paris & Sullivan, 1992), and no

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studies reported ankle abduction–adduction. This gap is partly explained by the distribution of mechanical work during gait, which is predominantly sagittal at the ankle joint (Tabucol et al., 2022). However, it also reflects fundamental biomechanical constraints of the ankle–foot complex. The talocrural joint primarily supports sagittal-plane motion, while frontal- and transverse-plane motions arise from distributed coupling across the subtalar and midfoot joints, limiting the ability to isolate single-plane forces (McKeon & Hoch, 2019; Nester et al., 2007). Transverse-plane motions are not governed by a single dominant anatomical axis, further complicating consistent measurement and interpretation. Future work may benefit from multi-body kinematic decomposition methods, such as Euler-angle–based approaches, to better resolve coupled joint motion into independent components for force estimation.

Several methodological limitations should also be considered. First, variability in force measurement protocols, particularly dynamometer placement and testing posture, likely contributed to heterogeneity across studies, even when nominally measuring the same joint action (Table 3). In some cases, insufficient reporting of measurement setup further limited reproducibility and comparability. Second, the inclusion of heterogeneous adult populations without restrictions on age or activity level increases variability but reduces specificity to any single subgroup. While this enhances generalizability, it also means mean values should not be interpreted as representative of any specific population segment. Despite these limitations, the resulting dataset provides a consolidated reference framework for peak lower-limb force production and supports its application in the design and optimization of lower-limb robotic exoskeleton systems.

Conclusion

This literature review consolidated published data to establish a normative reference framework of peak lower-limb force values for application in the design of robotic exoskeleton systems. In total, 17 studies were included to define a solution space across seven degrees of freedom of the lower limb, comprising three degrees of freedom each at the hip and ankle, and one at the knee joint. The resulting dataset provides complete coverage for five of the seven degrees of freedom, including sagittal-plane movements at the hip, knee, and ankle, as well as hip frontal and transverse plane movements. However, a gap remains in the ankle frontal and transverse planes due to limited available literature. This gap is primarily attributable to the complex structure of the ankle–foot complex, which limits the ability to isolate non-sagittal plane forces using conventional measurement approaches. Future work should therefore focus on developing Euler angle–based

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or equivalent multi-planar decomposition methods to better resolve coupled ankle motions and enable more robust estimation of peak force values across all degrees of freedom.

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References

Andrews, A. W., Thomas, M. W., & Bohannon, R. W. (1996). Normative Values for Isometric Muscle Force Measurements Obtained With Hand-held Dynamometers. *Physical Therapy*, *76*(3), 248–259. https://doi.org/10.1093/ptj/76.3.248

Bäckman, E., Johansson, V., Häger, B., Sjöblom, P., & Henriksson, K. (2013). Isometric muscle strength and muscular endurance in normal persons aged between 17 and 70 years. *Journal of Rehabilitation Medicine*, *27*(2), 109–117. https://doi.org/10.2340/165019772109117

Douma, R. K., Soer, R., Krijnen, W. P., Reneman, M., & Van Der Schans, C. P. (2014). Reference values for isometric muscle force among workers for the Netherlands: A comparison of reference values. *BMC Sports Science, Medicine and Rehabilitation*, *6*(1), 10. https://doi.org/10.1186/2052-1847-6-10

Eng, J. J., & Winter, D. A. (1995). Kinetic analysis of the lower limbs during walking: What information can be gained from a three-dimensional model? *Journal of Biomechanics*, *28*(6), 753–758. https://doi.org/10.1016/0021-9290(94)00124-M

Escarabajal, R. J., París, E., Jamšek, M., Petrič, T., Valera, Á., Mata, V., & Babič, J. (2026). Muscle-Targeted Robotic Assistance and Augmentation of Human Motion. *IEEE Transactions on Cybernetics*, *56*(2), 644–656. https://doi.org/10.1109/TCYB.2025.3623064

Fukunaga, T., Roy, R. R., Shellock, F. G., Hodgson, J. A., Day, M. K., Lee, P. L., Kwong-Fu, H., & Edgerton, V. R. (1992). Physiological cross-sectional area of human leg muscles based on magnetic resonance imaging. *Journal of Orthopaedic Research*, *10*(6), 926–934. https://doi.org/10.1002/jor.1100100623

Gomez, R. A. E., Destarac Eguizabal, M. A., Gutierrez, M. N. C., Montano, J. G., Herrera, M. C. S., Acebron, R., Puglisi, L. J., & Cena, C. E. G. (2017). ORTE exoskeleton: Actuation system dimensioning and selection. *2017 IEEE 37th Central America and Panama*

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Convention (CONCAPAN XXXVII), 1–6. https://doi.org/10.1109/CONCAPAN.2017.8278493

Greve, D., & Kreischer, C. (2024). Methodology for Integrated Design Optimization of Actuation Systems for Exoskeletons. *Robotics*, *13*(11), 158. https://doi.org/10.3390/robotics13110158

Heijboer, W. M. P., Thijs, K. M., Weir, A., Serner, A., Tol, J. L., Goedhart, E. A., & Groot, F. P. (2024). Normal hip strength and range of motion values in youth and adult female national football teams: Data from 504 assessments. *Physical Therapy in Sport*, *69*, 51–58. https://doi.org/10.1016/j.ptsp.2024.06.005

Hoglund, L. T., Wong, A. L. K., & Rickards, C. (2014). The impact of sagittal plane hip position on isometric force of hip external rotator and internal rotator muscles in healthy young adults. *International Journal of Sports Physical Therapy*, *9*(1), 58–67.

Hunter, S. K., Pereira, H. M., & Keenan, K. G. (2016). The aging neuromuscular system and motor performance. *Journal of Applied Physiology*, *121*(4), 982–995. https://doi.org/10.1152/japplphysiol.00475.2016

Huysamen, K., Power, V., & O'Sullivan, L. (2020). Kinematic and kinetic functional requirements for industrial exoskeletons for lifting tasks and overhead lifting. *Ergonomics*, *63*(7), 818–830. https://doi.org/10.1080/00140139.2020.1759698

Izquierdo, M., Häkkinen, K., Gonzalez-Badillo, J., Ibáñez, J., & Gorostiaga, E. (2002). Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. *European Journal of Applied Physiology*, *87*(3), 264–271. https://doi.org/10.1007/s00421-002-0628-y

Jaric, S. (2002). Muscle Strength Testing: Use of Normalisation for Body Size. *Sports Medicine*, *32*(10), 615–631. https://doi.org/10.2165/00007256-200232100-00002

DRAFT

Krähenbühl, N., Horn-Lang, T., Hintermann, B., & Knupp, M. (2017). The subtalar joint: A complex mechanism. *EFORT Open Reviews*, *2*(7), 309–316. https://doi.org/10.1302/2058-5241.2.160050

Martín-Miguel, I., Torrontegi-Ronco, E., Martínez-Ortega, J. D. D., Moreno-Martín, A., & Montalvo-Zenarruzabeitia, Z. (2025). Relative Values of Maximal Isometric Strength in Lower Limbs Across Different Sports Disciplines in High-Performance Athletes. *Journal of Strength & Conditioning Research*, *39*(8), e982–e990. https://doi.org/10.1519/JSC.0000000000005126

McKay, M. J., Baldwin, J. N., Ferreira, P., Simic, M., Vanicek, N., Burns, J., For the 1000 Norms Project Consortium, 1000 Norms Project Consortium, Baldwin, J., McKay, M., Ferreira, P., Nightingale, E., Pourkazemi, F., Sman, A., Hiller, C., Mousavi, S., Nicholson, L., Rose, K., Chard, A., … Quinlan, K. (2017). Normative reference values for strength and flexibility of 1,000 children and adults. *Neurology*, *88*(1), 36–43. https://doi.org/10.1212/WNL.0000000000003466

Medina McKeon, J. M., & Hoch, M. C. (2019). The Ankle-Joint Complex: A Kinesiologic Approach to Lateral Ankle Sprains. *Journal of Athletic Training*, *54*(6), 589–602. https://doi.org/10.4085/1062-6050-472-17

Meldrum, D., Cahalane, E., Conroy, R., Fitzgerald, D., & Hardiman, O. (2007). Maximum voluntary isometric contraction: Reference values and clinical application. *Amyotrophic Lateral Sclerosis*, *8*(1), 47–55. https://doi.org/10.1080/17482960601012491

Miehling, J. (2019). Musculoskeletal modeling of user groups for virtual product and process development. *Computer Methods in Biomechanics and Biomedical Engineering*, *22*(15), 1209–1218. https://doi.org/10.1080/10255842.2019.1651296

Nester, C., Jones, R. K., Liu, A., Howard, D., Lundberg, A., Arndt, A., Lundgren, P., Stacoff, A., & Wolf, P. (2007). Foot kinematics during walking measured using bone and surface

DRAFT

mounted markers. *Journal of Biomechanics*, *40*(15), 3412–3423. https://doi.org/10.1016/j.jbiomech.2007.05.019

Ogihara, N., Seki, H., Sujino, A., Ito, A., Matsumoto, Y., Suwa, G., Nagura, T., Yokoyama, Y., Yamada, M., Yamada, Y., & Jinzaki, M. (2026). Three-dimensional in vivo kinematics of the subtalar joint during weight-bearing standing on coronal-wedge surfaces using upright computed tomography. *Gait & Posture*, *123*, 110021. https://doi.org/10.1016/j.gaitpost.2025.110021

Oliveira, I. O. D., Pilz, B., Santos, R. L. G., Vasconcelos, R. A., Mello, W., & Grossi, D. B. (2018). Reference values and reliability for lumbopelvic strength and endurance in asymptomatic subjects. *Brazilian Journal of Physical Therapy*, *22*(1), 33–41. https://doi.org/10.1016/j.bjpt.2017.09.008

Paris, D. L., & Sullivan, S. J. (1992). Isometric Strength of Rearfoot Inversion and Eversion in Nonsupported, Taped, and Braced Ankles Assessed by a Hand-Held Dynamometer. *Journal of Orthopaedic & Sports Physical Therapy*, *15*(5), 229–235. https://doi.org/10.2519/jospt.1992.15.5.229

Pasco, J. A., Stuart, A. L., Holloway-Kew, K. L., Tembo, M. C., Sui, S. X., Anderson, K. B., Hyde, N. K., Williams, L. J., & Kotowicz, M. A. (2020). Lower-limb muscle strength: Normative data from an observational population-based study. *BMC Musculoskeletal Disorders*, *21*(1), 89. https://doi.org/10.1186/s12891-020-3098-7

Phillips, B. A., Lo, S. K., & Mastaglia, F. L. (2000). Muscle force measured using [ldquo]break[rdquo] testing with a hand-held myometer in normal subjects aged 20 to 69 years. *Archives of Physical Medicine and Rehabilitation*, *81*(5), 653–661. https://doi.org/10.1053/mr.2000.4413

Sandler, J., Pacecca, E., Kennedy, R., & Bonanno, D. R. (2025). Normative and correlation data of hip and groin strength in professional male Australian football players. *Sport Sciences for Health*, *21*(1), 217–223. https://doi.org/10.1007/s11332-024-01249-x

DRAFT

Stoll, T., Huber, E., Seifert, B., Michel, B. A., & Stucki, G. (2000). Maximal Isometric Muscle Strength: Normative Values and Gender-Specific Relation to Age. *Clinical Rheumatology*, *19*(2), 105–113. https://doi.org/10.1007/s100670050026

Tabucol, J., Kooiman, V. G. M., Leopaldi, M., Brugo, T. M., Leijendekkers, R. A., Tagliabue, G., Raveendranathan, V., Sotgiu, E., Benincasa, P., Oddsson, M., Verdonschot, N., Carloni, R., & Zucchelli, A. (2022). The Functionality Verification through Pilot Human Subject Testing of MyFlex-δ: An ESR Foot Prosthesis with Spherical Ankle Joint. *Applied Sciences*, *12*(9), 4575. https://doi.org/10.3390/app12094575

The National Isometric Muscle Strength (NIMS) Database Consortium. (1996). Muscular weakness assessment: Use of normal isometric strength data. *Archives of Physical Medicine and Rehabilitation*, *77*(12), 1251–1255. https://doi.org/10.1016/S0003-9993(96)90188-4

Van Der Ploeg, R. J., Fidler, V., & Oosterhuis, H. J. (1991). Hand-held myometry: Reference values. *Journal of Neurology, Neurosurgery & Psychiatry*, *54*(3), 244–247. https://doi.org/10.1136/jnnp.54.3.244

Vannatta, C. N., & Kernozek, T. W. (2021). Normative Measures of Hip Strength and Relation to Previous Injury in Collegiate Cross-Country Runners. *Journal of Athletic Training*, *56*(10), 1072–1077. https://doi.org/10.4085/721-20

Warneke, K., Wagner, C.-M., Keiner, M., Hillebrecht, M., Schiemann, S., Behm, D. G., Wallot, S., & Wirth, K. (2023). Maximal strength measurement: A critical evaluation of common methods—a narrative review. *Frontiers in Sports and Active Living*, *5*, 1105201. https://doi.org/10.3389/fspor.2023.1105201

Xu, T., Sun, Z., Li, S., Tang, H., Zhang, Y., Tong, R. K., Meng, Q., & Yu, H. (2025). Adjustable-Stiffness Hip Exoskeleton with Flexible Energy-Storage Module for 3D Gait Correction. *Machines*, *13*(10), 959. https://doi.org/10.3390/machines13100959

DRAFT

Yandell, M. B., Ziemnicki, D. M., McDonald, K. A., & Zelik, K. E. (2020). Characterizing the comfort limits of forces applied to the shoulders, thigh and shank to inform exosuit design. *PLOS ONE*, *15*(2), e0228536. https://doi.org/10.1371/journal.pone.0228536

DRAFT