Innovations Health Devices 2026

White Paper – Range of Motion

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

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Introduction

Range of motion (ROM) is a biomechanical measurement that describes the angular displacement available at a joint within a movement plane (Abu El Kasem et al., 2020). ROM are widely used across clinical, rehabilitative, and engineering applications. In clinical settings, ROM assessments help evaluate joint mobility and identify potential musculoskeletal impairments or abnormalities (Shultz et al., 2016; Soucie et al., 2011). Within rehabilitation, ROM measurements are used to monitor recovery progress, evaluate treatment effectiveness, and assess readiness to return to daily activities or sport (Gerhardt & Rondinelli, 2001). Additionally, ROM measurements are integral to engineer prosthetic devices, exoskeleton and wearable product design, or to create ergonomic products or workspaces (An, 1984; Pinto-Fernandez et al., 2020; Becker & Thakor, 1988).

Accurate ROM data is especially important in the development of exoskeletons and robotic systems intended to replicate or support human movement. Understanding normative lower-limb movement patterns through ROM data is critical for the development of robotic exoskeletons (Pinto-Fernandez et al., 2020). These machines must be engineered with a comprehensive understanding of the biomechanics of the hip, knee, and ankle joints, recognizing that each joint exhibits distinct degrees of freedom and characteristic ranges of motion (Pinto-Fernandez et al., 2020). As a biomechanical measurement, ROM data quantifies joint capabilities and human anthropometric information (Grimmer et al., 2020a).The quantification of these variables allows for the programming of robotic exoskeletons to produce similar movement capabilities as humans, resulting in lower-limb wearable robots moving in conjunction with the lower-limbs of the human participant (Grimmer et al., 2020a).For example, human gait biomechanics, including joint angles or torques throughout the gait cycle, are necessary for determining the way an exoskeleton must move to assist the user (Pinto-Fernandez et al., 2020). Any discrepancies between the human joint and exoskeleton joint can limit the user's voluntary ROM and produce unwanted forces (Massardi et al., 2022). Additionally, these discrepancies may exceed the participants ROM, causing strains or other injuries (Massardi et al., 2022).

While a substantial body of literature exists reporting joint ROM values, these findings are dispersed across individual studies, making it challenging to compare and analyze this data. Within literature, normative ROM datasets tend to be fragmented, reporting only on specific lower-limb joints or select degrees of freedom. This fragmentation leads to inconsistences and gaps in comprehensive biomechanical understanding, limiting the applicability of this data.

Additionally, within the context of creating a lower-limb robotic exoskeleton, insufficient ROM accommodation can restrict movement, increase discomfort, alter gait, or create unsafe human-device interaction (Massardi et al., 2022). Therefore, a comprehensive normative ROM database is essential for the effective design of lower-limb robotic exoskeletons.

The purpose of this literature review is to create a consolidated normative ROM reference database, categorized according to the primary degrees of freedom of the lower-limb joints. This database is intended for use in biomechanical modeling and in guiding the design of lower-limb assistive technologies, including robotic exoskeletons. The scope of this review is limited to ROM values reported in healthy adults with no reported history of musculoskeletal injury or surgery and are intended to represent normative ranges within this population.

Methods

From December 4th, 2025, to December 17th, 2025, a web-based literature review was conducted to find scientific papers describing single-plane ROM values at the lower-limb joints for healthy adults. For the purpose of this review, seven degrees of freedom were analyzed across the hip, knee, and ankle joints (Table 1). Reviewed publications were published between January 1st, 1980, to November 30th, 2025, and were gathered from three web-based databases: SPORTDiscus, Ovid, and PubMed.

All studies were in the English language. For all three databases, key search terms included: (range of motion OR rom OR range of movement OR flexibility) AND (hip OR knee OR ankle) AND (sagittal OR transverse OR frontal) AND (normal OR healthy OR typical) AND (goniometer OR inclinometer OR kinematic) NOT (children OR adolescents OR youth OR child OR teenage) NOT (replacement OR injury OR trauma OR surgery).

Studies reporting ROM values in populations with musculoskeletal injuries, prior surgery, or trauma were excluded from this review. Additionally, studies involving only children or adolescents were excluded. No restrictions were placed on the reported ROM measurement type (active or passive), assessment protocol, sex, or physical activity levels in order to capture a broad range of normative ROM values across healthy adult populations. All scientific articles identified through the search strategy underwent a three-stage screening process consisting of title review, abstract review, and a full-text review. Articles with titles deemed relevant advanced to abstract review, and studies with contextually relevant abstracts underwent full-text evaluation. Studies that successfully met the inclusion criteria following full-text review were included in this literature review.

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

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

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 ROM value or mean standard deviation and then divided by the total sample size. The minimum and maximum values were directly reported by each study. The smallest minimum and largest maximum value found in the literature was used for the absolute minimum and maximum values for each degree of freedom (Table 1).

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

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

Equation 1

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

Equation 2

All ROM values reported by studies meeting all inclusion criteria organized into a database by the name of the study, the joint (hip, knee, or ankle), the movement (flexion, extension, abduction, adduction, internal rotation, external rotation, dorsiflexion, plantarflexion, inversion, eversion) and if stated, the average age or gender of the sample population. The database was organized by each degree of freedom shown in Table 1.

For this review, “sufficient literature” was achieved if there were greater than 1500 data points with representation across both sexes and various ages. Each data point had a unique combination of the joint, movement plane, and age range. When studies reported additional demographic information such as race or information on which limb was reported (i.e. dominant or non-dominant), this information was included in the database, leading to additional unique combinations. The number of participants in each plane of motion and limb combination ranged from 6 to 1000, depending on the number of participants reported in each study.

Results

The search yielded 483 total results across three databases. The titles of all 483 scientific articles were reviewed, with 97 papers advancing to abstract review. Out of the 97 papers, 51 articles met the inclusion criteria. Full-text evaluation resulted in 29 contextually relevant papers. After a secondary review of reported ROM values identified 13 out of 29 papers explicitly reported on single-plane ROM values at the hip, knee, or ankle joints. Values reported from the 13 papers that met all inclusion criteria were used in this review (Figure 1).

Thirteen studies reported single-plane ROM values (Table 2). The total pooled sample size across all studies was N = 3855, consisting of 49% male participants (N = 1878) and 47% female participants (N = 1816). Participant sex was unreported for 4% of the sample (N = 162), however the authors noted that both male and female participants were included (Kumar 2011). These included scientific articles were published between 1981 – 2024 (Table 2). Eight studies (Abu El Kasem et al., 2020; Hallaceli et al., 2020; Heijboer et al., 2024; Kumar et al., 2020; Roaas & Andersson, 1982; Roach & Miles, 1991; Schwarz et al., 2011; Soucie et al., 2011) measured ROM values using a goniometer. Four studies used camera-based motion analysis systems, including three studies (Chester et al., 2016; Paquette et al., 2015; Yum et al., 2021) that implemented 8-10 camera motion analysis systems, and one study (Ericson et al., 1988) that used single camera video analysis. Finally, one study measured ROM using an inclinometer (Da Costa et al., 2021).

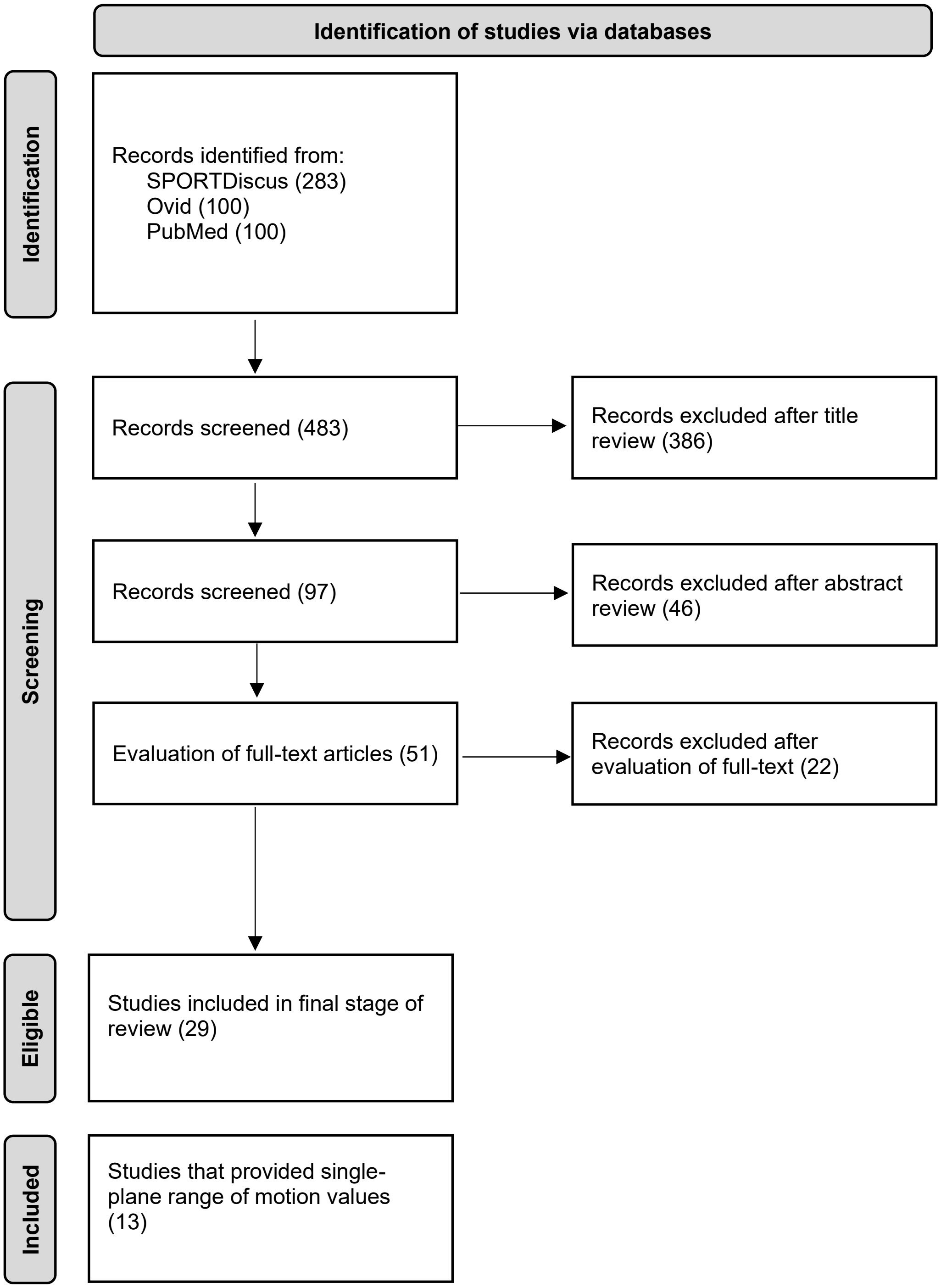

Figure 1 Flowchart of the literature review selection process.

Table 2 Summary of included studies

Study	Sample size	Joint	Movement	Sex	Age	Measurement System
Abu El Kasem et. al, 2020	1000	Hip	Flexion, Extension, Abduction, Adduction, Internal Rotation, External Rotation	Male: 500 Female: 500	18-30	Goniometer
		Knee	Flexion, Extension			
		Ankle	Dorsiflexion, Plantarflexion, Inversion, Eversion			
Chester et. al, 2016	16	Hip	Flexion, Extension, Abduction, Adduction	Male: 8 Female: 8	21-32	8-camera motion analysis system
		Knee	Flexion, Extension			
Ericson et. al, 1988	6	Hip	Flexion, Extension	Male: 6 Female: 0	20-31	16 mm cine-film camera (Paillard Bolex, 60 frameslsec)
		Knee	Flexion, Extension			
		Ankle	Dorsiflexion, Plantarflexion			
Da Costa et al., 2021	30	Ankle	Dorsiflexion	Male: 16 Female: 14	21-31	Inclinometer
Hallaceli et al., 2020	987	Hip	Flexion, Extension, Adduction, Internal Rotation, External Rotation	Male: 513 Female: 474	19-32	Goniometer
		Knee	Flexion, Extension			
		Ankle	Dorsiflexion, Plantarflexion, Inversion, Eversion			
Heijboer et al., 2024	344	Hip	Internal Rotation, External Rotation	Male: 0 Female: 344	18-20	Goniometer
Kumar et al., 2020	161	Hip	Flexion, Abduction, External Rotation, Internal Rotation	Males: N/A Females: N/A	15-100	Goniometer
		Ankle	Dorsiflexion, Plantarflexion			
Paquette et al., 2015	16	Hip	Flexion, Extension, Abduction, Adduction, External Rotation	Male: 16 Female: 0	21-24	10-camera motion analysis system
		Knee	Flexion, Extension			
Roaas & Andersson, 1982	365	Hip	Flexion, Extension, Abduction, Adduction, Internal Rotation, External Rotation	Male: 365 Female: 0	30-40	Goniometer
		Knee	Flexion, Extension			
		Ankle	Dorsiflexion, Plantarflexion, Inversion, Eversion			
Roach & Miles, 1991	323	Hip	Flexion, Extension, Abduction, Internal Rotation, External Rotation	Male: 162 Female: 161	25-74	Goniometer
		Knee	Flexion			
Schwarz et al., 2011	100	Ankle	Inversion, Eversion	Male: 50 Female: 50	19-25	Goniometer
Soucie et al., 2011	476	Hip	Flexion, Extension	Male: 219 Female: 257	20-69	Goniometer
		Knee	Extension			
		Ankle	Dorsiflexion, Plantarflexion			
Yum et al., 2021	31	Hip	Flexion, Extension, Abduction, Adduction, Internal Rotation, External Rotation	Male: 23 Female: 8	18-68	10-camera motion analysis system
		Knee	Flexion, Extension			
		Ankle	Dorsiflexion, Plantarflexion, Inversion, Eversion, Abduction, Adduction			

While there were 3855 participants across all 13 studies, many studies reported on both the dominant and non-dominant limb, often doubling the measurements obtained. Additionally, most studies (10/13) reported on ROM values across multiple lower limb joints, resulting in a total of 18,283 measurement data points. The distribution of these data points is summarized in Table 3.

Table 3 Number of data points for each plane of movement across the lower-limb joints

Joint	Movement	Data Points
Hip	Flexion/Extension	4454
	Abduction/Adduction	2171
	Internal Rotation/External Rotation	3854
Knee	Flexion/Extension	2756
Ankle	Dorsiflexion/Plantarflexion	2904
	Inversion/Eversion	2048
	Abduction/Adduction	-

ROM measurements (minimum, maximum, mean, and standard deviation) extracted from each study were compiled into a database and organized by each joint and movement combination outlined in Table 1. This data was used to calculate the overall minimum, maximum, mean, and standard deviation for each single-plane lower limb movement (Table 4). Using the summarized data from Table 4, plots were created in MATLAB to visualize the distribution of data within each movement plane (Figures 2-7). Due to a lack of literature reporting transverse-plane ankle ROM no corresponding figure was created.

Table 4 Weighted average range of motion values summarized from scientific literature (°)

Joint	Movement	Minimum	Maximum	Mean	SD
Hip	Flexion	106.0	133.8	121.7	6.6
	Extension	9.4	28.0	17.1	3.8
	Abduction	32.1	45.7	40.0	4.1
	Adduction	13.7	30.5	23.4	6.0
	Internal Rotation	25.0	44.4	32.9	5.5
	External Rotation	27.0	48.0	36.4	6.7
Knee	Flexion	132.6	148.9	139.9	5.4
	Extension	0.0	10.0	3.6	3.2
Ankle	Dorsiflexion	2.0	23.9	16.6	4.3
	Plantarflexion	13.0	63.1	43.4	13.0
	Inversion	9.0	35.3	27.7	10.0
	Eversion	2.6	19.9	14.0	6.5
	Abduction	-	-	-	-
	Adduction	-	-	-	-

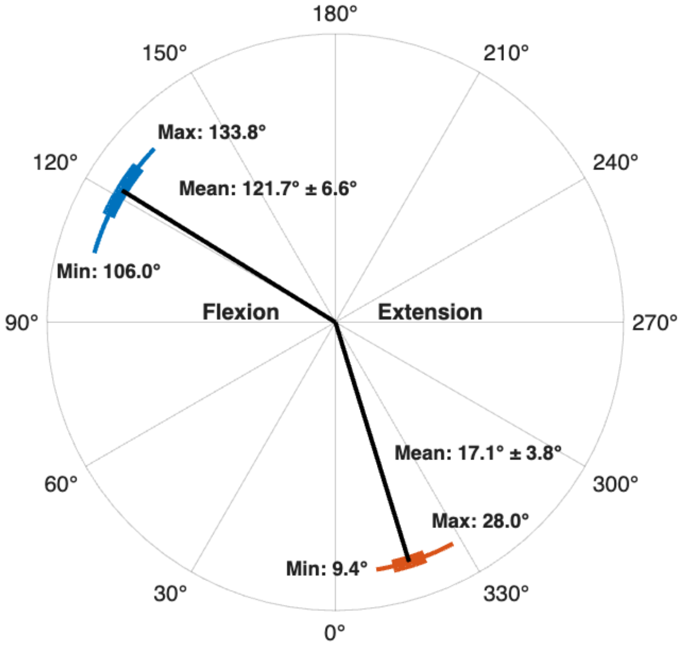

Figure 2 Summary of Range of Motion Values for Hip Flexion and Extension. Neutral position is represented by 0°. Thin blue (flexion; positive angles) and red (extension; negative angles) arcs indicate the minimum and maximum values reported across studies, whereas the corresponding thick arcs represent the mean ± standard deviation for each movement. Black radial lines denote the mean angle for hip flexion and extension.

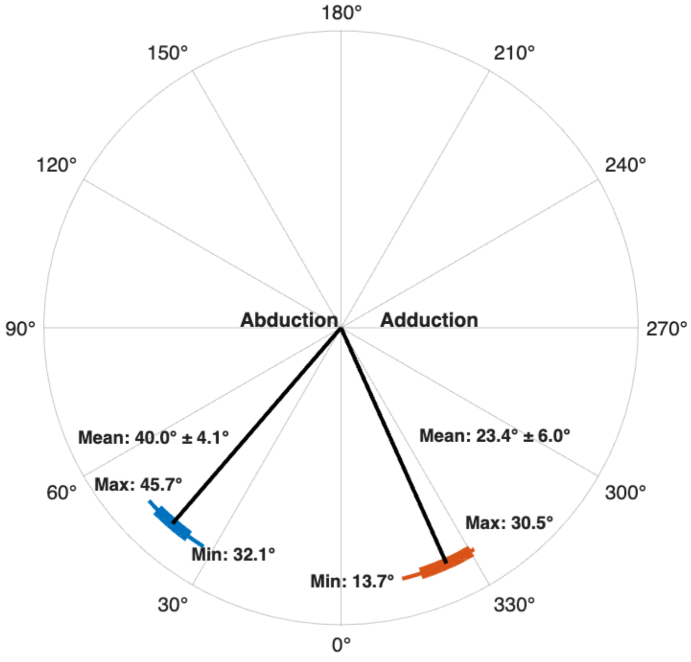

Figure 3 Summary of Range of Motion Values for Hip Abduction and Adduction. Neutral position is represented by 0°. Thin blue (abduction; positive angles) and red (adduction; negative angles) arcs indicate the minimum and maximum values reported across studies, whereas the corresponding thick arcs represent the mean ± standard deviation for each movement. Black radial lines denote the mean angle.

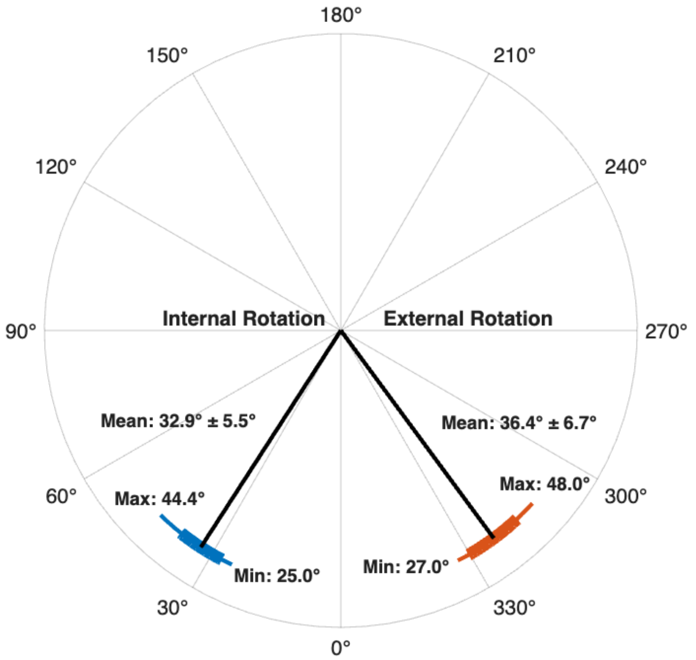

Figure 4 Summary of Range of Motion Values – Hip Internal and External Rotation. Neutral position is indicated at 0°. The thin blue (internal rotation, positive) and red (external rotation, negative) arcs represent the minimum and maximum values, while the thick arcs show the mean ± standard deviation for each movement. Finally, the corresponding black radial lines indicate the mean angle.

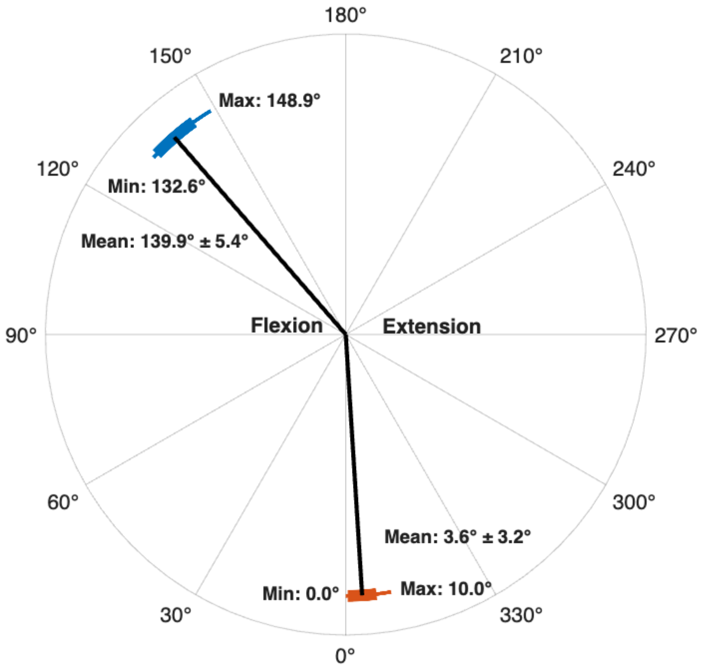

Figure 5 Summary of Range of Motion Values – Knee Flexion and Extension. Neutral position is indicated at 0°. The thin blue (flexion, positive) and red (extension, negative) arcs represent the minimum and maximum values, while the thick arcs show the mean ± standard deviation for each movement. Finally, the corresponding black radial lines indicate the mean angle.

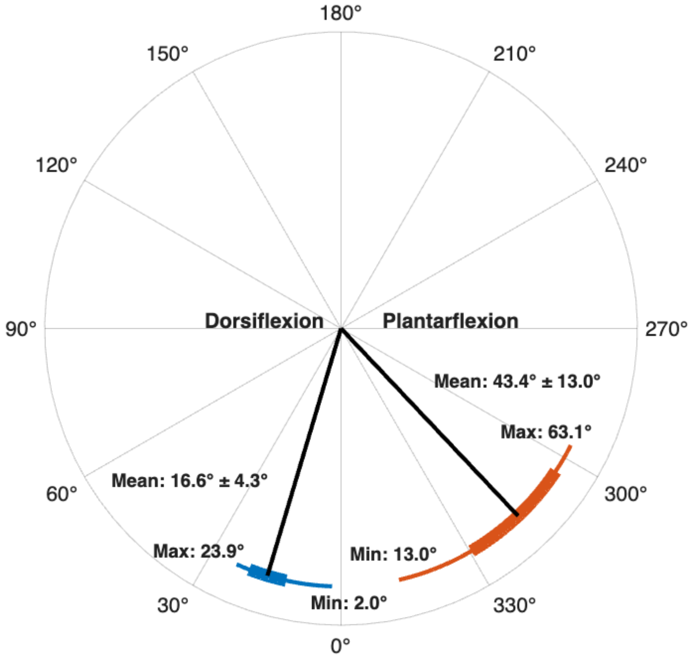

Figure 6 Summary of Range of Motion Values for Ankle Dorsiflexion and Plantarflexion. Neutral position is represented by 0°. Thin blue (dorsiflexion; positive angles) and red (plantarflexion; negative angles) arcs indicate the minimum and maximum values reported across studies, whereas the corresponding thick arcs represent the mean ± standard deviation for each movement. Black radial lines denote the mean angle.

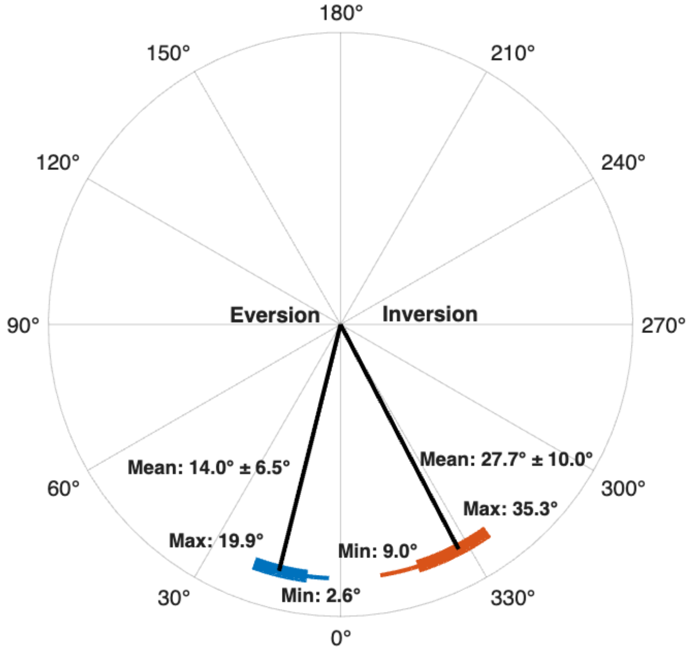

Figure 7 Summary of Range of Motion Values for Ankle Eversion and Inversion. Neutral position is represented by 0°. Thin blue (eversion; positive angles) and red (inversion; negative angles) arcs indicate the minimum and maximum values reported across studies, whereas the corresponding thick arcs represent the mean ± standard deviation for each movement. Black radial lines denote the mean angle.

Discussion

The goal of this literature review was to develop a solution space for single-plane ROM values at the hip, knee, and ankle joints. A total of 483 papers were reviewed, resulting in the inclusion of 13 papers with a total sample size of 3855. Following review of the available literature, the final solution space for ROM consisted of three degrees of freedom at the hip joint, one at the knee joint, and three at the ankle joint (Table 1).

Standard deviations varied across joints and movements. While there was low variability for hip and knee range of motions, ankle ROM had the greatest inconsistency between studies. Overall, the standard deviation for the hip ROM ranged between 3.82° to 6.69° while the standard deviation for the knee ROM values ranged between 3.16° to 5.36° (Table 4). Ankle ROM showed a wider spread, spanning from 4.29° to 13.00°. Ankle plantarflexion (SD = 13.00°) and ankle inversion (SD = 10.00°) showed the greatest variability, likely due to the inclusion of a study that measured ROM values during cycling movements.

The ROM metrics reported across the hip, knee, and ankle joints provide critical insights into the kinematic compatibility and operational boundaries of a lower-limb robotic exoskeleton. The hip joint demonstrated great flexibility, where the mean flexion (121.7° ± 6.58°) and extension (17.1° ± 3.82°) aligned closely with the range of motion requirements of standard sagittal-plane movements (Table 4) (Sah, 2022), The calculated mean hip abduction (40.0° ± 4.13°) from this literature review is slightly higher than one robotic exoskeleton found during a simulated clinical hip exam (37.7°) at 0° flexion (Goldsmith et al., 2015). This slight discrepancy is likely due to the fact that this study used cadaveric hips instead of living subjects, causing less active muscle contribution and a lower stress tolerance, resulting in a lower hip abduction ROM. Contrastingly, the hip adduction ROM value synthesized from this literature review (23.4° ± 6.02°) was higher than the ROM reported from the robotic cadaveric testing (7.1°) (Table 4) (Goldsmith et al., 2015). As mentioned above, this difference likely resulted from the use of cadaveric hips, allowing the robot reliably to measure only hip adduction ROM. Unlike living subjects, where muscles and ligaments influence joint motion, cadaveric hips mounted in robotic systems lack these dynamic effects. As a result, these robotic systems measure hip abduction ROM in true isolation and removes the possibility that the participants may not have had a truly neutral position or shifted weight at the time of measurement (Goldsmith et al., 2015). Both hip internal rotation (32.9° ± 5.48°) and external rotation (36.4° ± 6.69°) measured in vivo were comparable with cadaveric robotic findings, suggesting that these values can be used to guide the specification of hip rotational limits and control parameters in lower-limb exoskeletons. Additionally, while the values reported in this literature review were only for single-plane movements, combination movements resulted in higher hip abduction, adduction, external rotation, and internal rotation ROM values (Goldsmith et al., 2015). This highlights the need for robotic exoskeletons to account for coupled, multi-planar variability in ROM.

Knee flexion (139,9° ± 5,36°) and extension (3.6° ± 3.16°) in living subjects aligned with biomechanical requirements identified in literature, suggesting that these values can inform the specification of knee joint limits and thresholds in lower-limb exoskeletons (Table 1) (Grimmer et al., 2020b). Ankle dorsiflexion (16.6° ± 4.29°) measured in living subjects aligned with typical functional ranges reported in the literature (Table 4) (Grimmer et al., 2020b). However, higher dorsiflexion demands of up to approximately 38° were identified during higher-demand activities, indicating that exoskeleton design must consider higher ankle dorsiflexion ROM beyond the baseline values provided (Grimmer et al., 2020b). Ankle inversion (27.7° ± 10,01°) and eversion (14.0° ± 6.45°) reflect the restricted range of frontal plane motion incorporated in ankle exoskeletons (ankle inversion and eversion ≈ ± 30°). This ROM constrains joint design to relatively small rotational limits while ensuring proper alignment with the subtalar joint axis to avoid unintended joint loading and discomfort (Table 4) (Jacobson et al., 2025).

There were no studies that reported on ankle abduction and adduction, resulting in a large gap in the ROM solution space for ankle movements in the transverse plane (Table 4). Since these movements are not typically measured by dynamometers, measuring these movements would likely require motion capture or camera analysis systems. However, the anatomical structure of the ankle-foot complex inherently limits accurate measures of the full ROM in the transverse plane.

Within the ankle-foot complex, the primary motion at the talocrural joint occurs in the sagittal plane, making it simpler to quantify dorsiflexion and plantarflexion (Medina McKeon & Hoch, 2019). Similarly, inversion and eversion are considered the main clinically assessed motions at the subtalar joint (Krähenbühl et al., 2017). It is important to note that the subtalar joint moves about an oblique axis and therefore involves all movement planes, but the primary movements that occur at this joint are in the frontal plane (Ogihara et al., 2026). This clear separation of primary motion between joints allows easier isolation in both the sagittal and frontal planes, resulting in consistent, clinically reliable measurements. There is no joint that exists within the ankle-foot complex whose primary motion occurs in the transverse plane, as transverse-plane rotation is a secondary component of motion distributed across the subtalar and midfoot joints, not along a specific movement axis (Nester et al., 2007). Since transverse plane movements at the ankle are coupled with movements occurring along other anatomical axes, they become difficult to reliably isolate and measure independently. This anatomical limitation causes complexities when attempting to measure movements in the transverse plane, even when using a motion capture or camera analysis system.

The three measurement techniques used in the studies covered in this literature review were goniometers, inclinometers, and camera analysis systems. Goniometers and inclinometers are both commonly used for measuring ankle ROM (Konor et al., 2012). While both are less expensive than a camera-based system, goniometers tend to be cheaper than an inclinometer, but requires the greatest technical competence (Konor et al., 2012). Specifically, the clinician must position both arms at reference points while also aligning the measurement axis with the joint's center of rotation (Konor et al., 2012). By contrast, using an inclinometer only requires the clinician to identify key landmarks such as the tibial tuberosity or proximal aspect of the fifth metatarsal (Konor et al., 2012).Despite these differences in measurement techniques, both tools have been found to produce reliable ROM measurements when used by a beginner rater (Konor et al., 2012).

There are a few limitations to this review. Based on the inclusion and exclusion criteria, the ROM values extracted and analyzed were derived from healthy adults with no history of injury or surgery. Since there were no restrictions on sex or activity level, the resulting consolidated values are intended to be representative of the healthy adult population. While this data may not be representative of clinical populations, the ROM values for this population are included within the range of this study. By using healthy adults as the target population for this review, most populations that did not meet the inclusion criteria will have lower maximum ROM values. The pooled sample across all 13 studies included adequate representation of both sexes and a wide range of adult age groups (Table 2). Another limitation of this review is the assumption that the neutral joint position was 0° across all participants. While this convention is typically used when reporting lower-limb joint ROM values, true neutral alignment may differ between individuals due to anatomical differences or the posture of the individual at the time of testing. As a result, the values reported in this literature review may not fully account for subject-specific variations in resting joint orientation. However, investigating individualized neutral joint positions was outside the scope of this review and limited by the lack of consistently reported data within included studies.

Conclusion

This white paper synthesized data obtained from literature to establish normative ROM values across seven degrees of freedom within the lower limb. ROM data from thirteen studies were used to create a solution space for six out of seven degrees of freedom, with reported values including the minimum, maximum, mean, and standard deviation. This literature review provides a consolidated reference to support the practical application of ROM values within a clinical or industry-focused context. A major gap within this solution space was the lack of measurements reported for ankle abduction and adduction. Due to the structural limitations of the ankle-foot complex, movements that occur in the transverse plane are composite, making them difficult to isolate and accurately measure. Future studies could improve measurements of ankle ROM movements in the transverse plane using 3D motion capture systems or potentially isolating for subtalar joint contribution using bone-pin studies. Additionally, future studies could focus on identifying the normal ROM for clinical populations. Overall, this literature review bridged existing gaps in the literature by consolidating fragmented data into a reference for future research and applied biomechanics.

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