Published in *Gait & Posture*, 2016, vol. 50, pp. 239-245, which should be cited to refer to this work.
DOI: 10.1016/j.gaitpost.2016.09.016

Feasibility and reliability of using an exoskeleton to emulate muscle contractures during walking

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Acknowledgements

This study was founded by the Swiss National Science Foundation (SNF) project 325230_146801.

Abstract

Contracture is a permanent shortening of the muscle–tendon–ligament complex that limits joint mobility. Contracture is involved in many diseases (cerebral palsy, stroke, etc.) and can impair walking and other activities of daily living. The purpose of this study was to quantify the reliability of an exoskeleton designed to emulate lower limb muscle contractures unilaterally and bilaterally during walking.

An exoskeleton was built according to the following design criteria: adjustable to different morphologies; respect of the principal lines of muscular actions; placement of reflective markers on anatomical landmarks; and the ability to replicate the contractures of eight muscles of the lower limb unilaterally and bilaterally (psoas, rectus femoris, hamstring, hip adductors, gastrocnemius, soleus, tibialis posterior, and peroneus). Sixteen combinations of contractures were emulated on the unilateral and bilateral muscles of nine healthy participants. Two sessions of gait analysis were performed at weekly intervals to assess the reliability of the emulated contractures. Discrete variables were extracted from the kinematics to analyse the reliability.

The exoskeleton did not affect normal walking when contractures were not emulated. Kinematic reliability varied from poor to excellent depending on the targeted muscle. Reliability was good for the bilateral and unilateral gastrocnemius, soleus, and tibialis posterior as well as the bilateral hamstring and unilateral hip adductors. The exoskeleton can be used to replicate contracture on healthy participants. The exoskeleton will allow us to differentiate primary and compensatory effects of muscle contractures on gait kinematics.

Keywords: contracture, gait, exoskeleton, simulation, emulation, kinematics

Introduction

To be able to walk without feeling pain, fatigue, or another alteration is considered a priority in daily life and is linked to the quality of life [1, 2]. Numerous impairments in the neurological and/or musculoskeletal systems generate walking alterations. A precise understanding of these alterations is required to optimise therapeutic strategies. Among impairments, contractures in the lower limbs occur frequently and alter human walking [1, 2]. Contracture induces a restricted passive range of motion (ROM) [2, 3] as a result of limited extensibility or increased stiffness of the soft tissues around the joints such as ligaments, capsule, tendons and muscles [2]. Contractures have been reported in numerous pathologies such as cerebral palsy [4], multiple sclerosis, spinal cord injury and stroke [1]. Different mechanisms can be implicated in contractures, such as muscular shortening, shortening of ligaments, joint capsule alterations, intra-articular adhesions and proliferation of fibro-fatty tissues into the joint [5]. The main causes of contractures are immobilisation [6], muscle weakness [7] and spasticity [8]. The consequences of contractures on activities of daily life include walking deviations [9], loss of balance with risk of fall [1] and bone deformities affecting posture [10].

Experimental approaches have been used to induce the ROM limitations of joints using mechanical methods (rope, elastic, orthotics, and so on). Matjacic and Olensek [11] investigated biomechanical characterisation and the clinical implication of artificially induced crouch walking, and this approach allowed them to determine the extent to which the iliopsoas and hamstring are implicated in crouch walking. Goodman et al. [12] and Houx et al. [13] evaluated the compensation mechanisms of toe-walking unilaterally. They explained that in patients with hemiplegia, hip ROM limitations and knee extension in gait were not caused by hamstring and/or hip flexor contractures but were linked to ankle plantarflexor contractures only. Harato et al. [14] studied the influence of knee contractures on trunk kinematics and determined the minimum degree of contracture required to obtain a significant difference in trunk movements in gait. Whitehead et al. [15] emulated hamstring contracture with an exoskeleton at the hip and knee level. They determined that to have an effect on knee kinematics, the popliteal angle would need to exceed 85°. These different results provide an important understanding on pathologic gait and support the links between clinical examination and gait deviations. However, these studies were focused on one or two muscles. To our knowledge, no study has used an external system that is able to emulate a combination of contractures on the main muscular groups of the lower limb. Therefore, the purpose of this study was to quantify the reliability of an exoskeleton designed to emulate lower limb muscle contractures unilaterally and bilaterally during walking.

Method

Design exoskeleton:

An exoskeleton was built based on the method of Matjacic and Olensek [11] with the addition of certain criteria with:

Design criteria:

- Respects the main lines of action of the muscles.
- Is adjustable according to the anthropometry of participants.
- Avoids relative displacement between the plastic cuffs and the supporting body segment.
- Has the possibility to perform motion capture with reflective markers placed directly on the skin.

Assessed criteria:

- No modification of gait with the exoskeleton if no contractures were emulated.
- Can replicate contractures of the main lower limb muscles affected by contractures with a good level of reliability.

The exoskeleton was designed and built in collaboration with the Giglio Partners Orthopedie group based in Geneva, Switzerland. The exoskeleton, named "MIkE" for **M**uscle contracture **I**nduced by an **E**xos**k**eleton, is presented in Figure 1. It was built to bilaterally embrace the pelvis, the thigh and the shank with plastic cuffs and with modified shoes that included attachment points. A particular cut was made on the plastic cuffs to enable reflective markers to be placed directly on the skin as requested for clinical gait analysis (CGA). Moreover, this design enabled each participant to walk with and without the exoskeleton without removing any reflective marker.

The exoskeleton was built to induce unilateral and bilateral contractures in relation to the following main muscles or muscle groups affected by contractures in the lower body and identified in the literature: hamstring, iliopsoas, hip adductor, rectus femoris, gastrocnemius, soleus, tibialis posterior and peroneus [16-19]. Contractures were induced by ropes attached to rings. The characteristics of the ropes were chosen to avoid a sudden stop and to mimic a progressive increase of stiffness at the limit of the ROM as reported for muscle contractures [2]. Because muscle insertion points are usually deep and multiple, only the main muscle lines of action were used to define the ropes attached to the rings. To respect the anthropometry of the participants, two different sizes of exoskeleton were built.

Protocol:

Participants:

Nine healthy participants (6 females, 3 males) ages 18 to 35 years old (age: 27 ± 5.7 years; height: 1.70 m ± 0.09; weight 66.3 kg ± 7.8), with no known neurologic or orthopaedic problems, participated in this study. Ethical approval and participant consent were obtained before the data collection began.

Gait evaluation:

The participants were equipped with 34 reflective markers that were aligned to anatomical landmarks on the head, trunk and pelvis, and bilaterally on the arms, thighs, shanks and feet according to the full-body Plug-in-Gait model [20]. All participants were requested to walk along a 10-meter walkway at a spontaneous, self-selected speed. Kinematic recordings were performed with a 12-camera motion analysis system (Vicon Mx3, Vicon Peak, Oxford, UK). For the CGA, a minimum of three trials (corresponding to a minimum of three gait cycles) were averaged to produce a single angular displacement of the thorax, pelvis segments, and hip, knee, and ankle joints.

To emulate contractures in relation to patient contractures, the ROM from clinical examinations performed in patients who benefited of a CGA in our laboratory was analysed. The database including 985 patients with various pathologies (e.g., cerebral palsy [55%], idiopathic toe-walker [12%], clubfoot [7%], poliomyelitis [3%], neuropathy [3%], congenital flat foot [1%], spina bifida [1%] and various pathologies [18%]) affecting gait was analysed. The passive ROM, measured during clinical examination (maximum movement possible), was extracted for the following muscles: gastrocnemius, soleus, hamstring, rectus femoris and psoas. The percentiles of these ROM were computed and used to define the emulated contractures. The procedure to adjust the contracture was similar to the standard physical examination; with the patient lying on the examination table, we adjusted the ropes lengths for the desired limitation of movement with a goniometer [21]. For the contractures of the tibialis posterior and peroneus muscles, the ROM limitation was assessed in the clinical examination with three categories: normal, limited, and blocked. Contracture of the adductors could not be emulated at a set angle. Instead, maximum abduction was set to the angle reached by the participants when their legs were against each other (approximately 5° adduction). Sixteen combinations of contractures were emulated on nine healthy participants on unilateral and bilateral muscles (Table 1). Before data capture, the participants practised walking for 2–5 minutes for each experimental condition. Once the participant was thought to have found a reliable gait in relation with the experimental condition, we assessed his/her gait (2 trials of 10 meters each). After each experimental condition, a resting period of 2 minutes was proposed to the participant to avoid the effect of fatigue. After the end of all of the experimental conditions, the exoskeleton was removed (but not the markers) to assess the gait without the exoskeleton. The order to emulate the contractures was always the same for each participant and for the two sessions (in unilateral and bilateral: gastrocnemius, hamstring, rectus femoris, soleus, psoas, hip adductor, tibialis posterior and peroneus). For unilateral conditions, the left and right legs were alternatively changed for each condition. The duration for each session was approximately 4 hours with 18 gait conditions and one iteration for each emulated contracture. Two sessions of CGA were performed at weekly intervals to assess the reliability of the emulated contractures.

Data analysis and statistics:

First, to evaluate if the first assessed criterion was respected (no modification of gait with the exoskeleton if no contractures were emulated), a Wilcoxon test was performed on the gait profile score (GPS) [22] and walking speed between the condition of walking without the exoskeleton and the condition of walking with the exoskeleton without emulated contracture (right and left sides merged together). In addition, the root mean square error (RMSE) was computed between these two conditions for the following angles: pelvis and hip (sagittal, frontal, and transverse planes), knee and ankle (sagittal plane) and foot progression.

Second, to verify the second assessed criterion (exoskeleton can replicate contractures of the main lower limb muscles affected with a good reliability), the reliability of the exoskeleton with emulated contractures was analysed. For each emulated contracture, discrete parameters were extracted on the lower limb kinematics depending of the joint (ankle, knee, and hip) involved in the contracture and described in Table 2.

For each gait condition and each parameter, the intraclass correlation coefficient (ICC), standard error of measurement (SEM) ($\text{Standard deviation(SD)} \times \sqrt{(1 - \text{ICC})}$) and smallest detectable change (SDC) ($1.96 \times \text{SEM} \times \sqrt{2}$) [23-25] were computed between the two sessions to evaluate the reliability [23-25]. The ICC was evaluated according to the Shrout and Fleiss [26] scale (ICC < 0.4: poor reliability; ICC 0.4-0.75: fair to good reliability; ICC > 0.75: excellent reliability). In addition, Bland and Altman graphs were designed as a graphical approach to explore the reliability of the bias existing between the different conditions at a 1-week interval and provided the mean difference with the limit of agreement ($\text{mean difference} \pm \text{SD [difference]} * 1.96$) [27] to evaluate the precision within which 95% of the differences fall. To evaluate the difference between the two sessions, the RMSE for all conditions between the two sessions was computed and averaged for the following angles: pelvis and hip (sagittal, frontal, and transverse planes), knee and ankle (sagittal plane) and foot progression. When the emulated contracture was unilateral, one side was considered (ipsilateral contracture side). When emulated contractures were bilateral, both sides were considered.

The data analysis, statistics and figures were performed with MATLAB R2012b (MathWorks, Natick, Massachusetts, USA) and the open-source Biomechanical ToolKit package for MATLAB [28]. A $p < 0.05$ was considered to show a statistically significant difference.

Results

Gait reliability without emulated contractures

The GPS and walking speed showed no significant difference between the two conditions of gait with a p-value of 0.983 for GPS and a p-value of 0.071 for walking speed (Figure 2). The medians (first and third quartiles) are presented for the condition without the exoskeleton: GPS 4.5° (4-5.4°), walking speed 1.4 m/s (1.2-1.5 m/s); and with the exoskeleton: GPS 4.5°

(3.9-5.0°), walking speed 1.3 m/s (1.2-1.4 m/s). A mean RMSE for all of the considered angles (pelvis, hip, knee, and ankle) of 3.1° (± 0.9) was computed between these two conditions.

Gait reliability with emulated contractures

The results showed (Table 3) from fair to good (ICC: 0.4-0.75) to excellent (ICC: >0.75) reliability for gastrocnemius, soleus and tibialis posterior unilaterally and bilaterally, as well as hamstring bilaterally and hip adductor unilaterally. Rectus femoris, psoas and peroneus were less reliable with some parameters showing poor reliability (ICC < 0.4) and three were non-interpretable (negative value can appear when the within-group variance exceeds the between-group variance) highlighted in grey in Table 3. The SEM and SDC showed the lowest reliability for the rectus femoris bilateral in knee ROM (flex/ext), showing more than 9° of SEM. Bland and Altman graphs showed the differences between conditions at a 1-week interval. Most of the differences were within the limits of agreement, with a few displacements of the mean difference around zero (<8° for the adductor bilaterally and <5° for the other conditions), which indicates a good reliability at a 1-week interval between conditions. The RMSE (Table 3) showed that most results were between 3° and 6°. Only adductors showed results higher, with 6.9° for adductor unilateral and 7.9° for adductor bilateral.

Discussion

The aim of this study was to design an exoskeleton that is able to emulate gait contractures on healthy participants and to analyse the reliability of this tool. Our experimental approach offers the opportunity to isolate each contracture to understand its specific impact on gait. First, an exoskeleton was built according to selected design criteria, and we demonstrated that normal walking was not influenced when the exoskeleton was worn without any emulated contractures. Second, contractures were emulated with good repeatability on healthy participants using this exoskeleton for some muscles (gastrocnemius, soleus and tibialis posterior unilaterally and bilaterally, as well as hamstring bilaterally and hip adductor unilaterally). Schwartz et al. [29] showed that variability can be caused by different biases, such as inter-trial, inter-session and inter-therapist errors, and that natural variability exists in the gait of healthy persons but should not be confused with experimental error. In our study, the main causes of variability were anatomical landmark misplacement [30], soft tissue artefacts [31] and the exoskeleton installation and configuration.

In the gait analysis, experimental error can reach an SEM of approximately 5-6° for hip rotations and ≤4° for other angles [32]. In our study, one parameter exceeded an SEM of 6.2°, corresponding to the gait with bilateral emulation of contractures on the rectus femoris. Indeed, this can be explained by the fact that the rope can slide on the patella with the effect of changing the line of action and the level of contracture. In addition, the main line of action was difficult to respect for the muscles that have a small joint ROM such as the tibialis posterior, peroneus, and hip adductor. We observed that the emulation of these contractures can interact with other movements. For example, we observed that the emulations of hip adductors have a tendency to limit hip extension. These difficulties can explain the lower reliability for the adductor bilateral muscle (RMSE: 7.93), but they do not seem to have a high impact on the tibialis posterior and peroneus.

In the literature, other studies have used contracture emulation systems or imitations on healthy participants to better understand the effects of contracture on gait. Concerning the ankle joint, the triceps surae contracture has been evaluated in many studies [9, 12, 24, 33-38]. At the knee joint, the hamstring contracture has also been evaluated [11, 14, 15, 39-41]. Finally, at the hip joint, only one study has evaluated the effect of psoas contracture [11]. Most of the studies on the ankle have analysed only one side, and only two studies have evaluated bilateral knee flexion contracture [15, 39]. Further, it will be interesting to use MIkE to develop these lacking aspects by studying bilateral contractures with a large range of combinations. None of these studies has evaluated the influence of their emulated contracture systems on gait kinematics (evaluating walking with and without their tools or contracture systems), nor have any of these studies analysed the reliability of their system, with the exception of the study by Ota et al. [24]. With the support of a reliable emulated contracture system MIkE, future studies will provide new insights to understand the effects of contractures on gait. A further interesting approach using MIkE, might be to study the effect of artificially restricted movement on patients with neurologic disorders without contracture to observe how they could adapt this gait.

Limitations

The first limitation of this study concerns the inter-rater reliability, which was not evaluated. Actually, because of the complexity involved in adjusting the exoskeleton, only one rater has been trained in the use of the exoskeleton.

The second limitation concerns the exoskeleton. Indeed, despite the fact that this exoskeleton is adjustable according to the anthropometry of participants with two different sizes and Velcro attachments, we noticed a tendency of the exoskeleton to slide when it is used on subjects with a high body mass index, despite being designed with non-slip pads.

The third limitation concerns the choice of the ropes that mimic the passive properties of the muscle-tendon complex. The rope properties avoid a sudden blocking of the motion, but we have no measurement of these properties. The rope properties were also similar for all of the emulated contractures even if the muscle–tendon complex has different passive properties according to the muscles used [42].

The fourth limitation specifically concerns the different adaptation strategies and the different types of walking chosen by the participants when contractures were emulated on biarticular muscles. For example, gastrocnemius contracture can act on plantarflexion, knee flexion/extension, or a combination of both [36]. The rectus femoris and hamstring can influence hip flexion/extension, knee flexion/extension, or both [11]. These different gait strategies are very interesting to study and can increase the variability of the results. However, we did not designate the choice of adaptation, and we allowed participants to self-select their adaptation and their more comfortable gait. The choice of the adaptations could be driven by a mix between different strategies such as to minimise energy [43], to optimise forward progression [44], to assure balance and stability [45], and certainly other undiscovered strategies. In addition, adaptation to contractures in patients with neurologic impairments might be different, because they also have associated impairments such as weakness, spasticity, or selectivity deficit. Even if the results of emulated contracture do not represent the reality, they will permit us to better understand the links between contractures (assessed during clinical examination) and gait deviations. Finally, contracture adaptation time can play an important role in the choice of different gait strategies by participants, and our study analysed only immediate adaptations (<5 minutes of training).

Conclusion

An exoskeleton MIkE was built and evaluated to emulate contractures during walking. Good reliability was found for gastrocnemius, soleus, and the tibialis posterior unilaterally and bilaterally, as well as the hamstring bilaterally and hip adductor unilaterally. The rectus femoris, psoas and peroneus were less reliable. The results demonstrate that the replication of contractures on healthy participants using an exoskeleton permit us to better understand the effect of contractures on gait. However, one should be aware of the limits of this approach. The exoskeleton allows us to differentiate between the primary and compensatory effects of muscle contractures on gait kinematics.

Conflict of interest

There are no conflicts of interest associated with this research.

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Table 1: *Amount of emulated contractures for each muscle and associated movement/position to adjust the emulated contractures.*

Muscles	Amount of emulated contracture	Movements
Peroneus	Maximum	Foot eversion
Tibialis	Maximum	Foot inversion
Soleus	-10°*	Dorsiflexion (knee in flexion)
Gastrocnemius	-20°*	Dorsiflexion (knee in extension)
Hamstring	95°*	Unilateral popliteal angle (hip and knee in flexion, contralateral lower limb in extension)
Rectus femoris	-40°*	Hip extension (knee in flexion)
Hip adductor	5°*	Hip abduction (hip in extension, knee in flexion)
Psoas	-30°*	Hip extension (knee in extension)

** Based on the 1st percentile of ROM performed during clinical examination (database of 985 patients who performed a CGA in Geneva University Hospital).*

***Table 2**: discrete parameters extracted on the lower limb kinematics depending of the joint (ankle, knee and hip) involved in the contracture*

	Ankle		**Foot**	**Knee**		**Hip**			
	Flex Ext IC	**Flex Ext ROM**	**Progression MP**	**Flex Ext IC**	**Flex Ext ROM**	**Flex Ext MP**	**Flex Ext ROM**	**Abd Add MP**	**Abd Add ROM**
Gastrocnemius	x	x	x	x	x				
Soleus	x	x	x						
Hamstring				x	x	x	x		
Rectus femoris				x	x	x	x		
Psoas						x	x	x	x
Hip adductor						x	x	x	x
Tibial posterior	x	x	x						
Peroneus	x	x	x						

x=measured parameters
IC = angle at initial contact; ROM = range of motion; MP = mean position angle
Flex/Ext = flexion / extension; Abd/Add = abduction / adduction

Table 3: Gait kinematics reliability for different emulated contractures between two sessions at weekly interval. ICC, SEM and SDC were computed for each contracture with involved joint (ankle, knee and hip). RMSE was computed based on the average of following angles: pelvis and hip (sagittal, frontal and transverse planes), knee and ankle (sagittal plane) and foot progression.

		Ankle		**Foot**	**Knee**		**Hip**			
	RMSE (°)	**Flex Ext IC**	**Flex Ext ROM**	**Progession MP**	**Flex Ext IC**	**Flex Ext ROM**	**Flex Ext MP**	**Flex Ext ROM**	**Abd Add MP**	**Abd Add ROM**
Gastrocnemius bilateral	4.32									
ICC		0.74	0.78	0.83	0.65	0.67	-	-	-	-
SEM(°)		3.12	2.09	2.38	4.95	5.02	-	-	-	-
SDC(°)		8.64	5.78	6.59	13.7	13.93	-	-	-	-
Gastrocnemius unilateral	4.52									
ICC		0.66	0.91	0.90	0.73	0.65	-	-	-	-
SEM(°)		4.93	1.70	1.80	4.50	6.16	-	-	-	-
SDC(°)		13.68	4.70	4.98	12.4	17.09	-	-	-	-
Soleus bilateral	4.06									
ICC		0.95	0.77	0.90	-	-	-	-	-	-
SEM(°)		1.45	1.80	2.50	-	-	-	-	-	-
SDC(°)		4.03	4.98	6.94	-	-	-	-	-	-
Soleus unilateral	5.02									
ICC		0.81	0.78	0.94	-	-	-	-	-	-
SEM(°)		1.65	2.84	1.02	-	-	-	-	-	-
SDC(°)		4.56	7.88	2.82	-	-	-	-	-	-
Hamstring bilateral	4.58									
ICC		-	-	-	0.89	0.77	0.95	0.83	-	-
SEM(°)		-	-	-	3.83	4.68	2.08	3.48	-	-
SDC(°)		-	-	-	10.6	12.97	5.77	9.65	-	-
Hamstring unilateral	4.44									
ICC		-	-	-	0.27	0.80	0.91	0.88	-	-
SEM(°)		-	-	-	6.03	4.65	2.40	2.42	-	-
SDC(°)		-	-	-	16.7	12.88	6.66	6.71	-	-
Rectus femoris bilateral	5.52									
ICC		-	-	-	0.69	0.56	0.91	0.58	-	-
SEM(°)		-	-	-	2.35	9.75	3.84	5.08	-	-
SDC(°)		-	-	-	6.51	27.01	10.66	14.09	-	-
Rectus femoris unilateral	6.07									
ICC		-	-	-	0.54	NI	0.86	0.47	-	-
SEM(°)		-	-	-	3.93	NI	4.65	5.54	-	-
SDC(°)		-	-	-	10.8	NI	12.88	15.35	-	-
Psoas bilateral	5.32									
ICC		-	-	-	-	-	0.28	0.77	0.40	0.63
SEM(°)		-	-	-	-	-	5.93	2.89	1.96	1.70
SDC(°)		-	-	-	-	-	16.45	8.01	5.42	4.70
Psoas unilateral	4.55									
ICC		-	-	-	-	-	0.25	0.51	0.70	0.62
SEM(°)		-	-	-	-	-	6.11	4.26	1.42	1.71
SDC(°)		-	-	-	-	-	16.92	11.80	3.95	4.74
Adductor bilateral	7.93									
ICC		-	-	-	-	-	0.76	0.86	NI	0.57
SEM(°)		-	-	-	-	-	5.38	2.84	NI	1.00
SDC(°)		-	-	-	-	-	14.92	7.86	NI	2.77
Adductor unilateral	6.92									
ICC		-	-	-	-	-	0.72	0.81	0.61	0.82
SEM(°)		-	-	-	-	-	5.09	3.47	2.79	0.91
SDC(°)		-	-	-	-	-	14.10	9.63	7.74	2.53
Tibial posterior bilateral	5.38									
ICC		0.91	0.76	0.78	-	-	-	-	-	-
SEM(°)		2.52	2.42	2.98	-	-	-	-	-	-
SDC(°)		6.97	6.72	8.26	-	-	-	-	-	-
Tibial posterior unilateral	4.71									
ICC		0.88	NI	0.84	-	-	-	-	-	-
SEM(°)		2.99	NI	3.34	-	-	-	-	-	-
SDC(°)		8.28	NI	9.26	-	-	-	-	-	-
Peroneus bilateral	5.54									
ICC		0.16	0.78	0.81	-	-	-	-	-	-
SEM(°)		5.23	3.21	4.99	-	-	-	-	-	-
SDC(°)		14.49	8.91	13.83	-	-	-	-	-	-
Peroneus unilateral	4.91									
ICC		0.26	0.90	0.88	-	-	-	-	-	-
SEM(°)		2.93	1.75	3.76	-	-	-	-	-	-
SDC(°)		8.12	4.84	10.42	-	-	-	-	-	-

ICC interpretation: excellent reliability = (> 0.75); fair to good reliability = (0.4-0.75); poor reliability = (< 0.4);
ICC = Intra-class correlation coefficient; SEM = Standard error of measurement; SDC = Smallest detectable change; IC= initial contact; ROM = range of motion; MP = mean position angle; NI = non-interpretable; RMSE = Root mean square error; Flex/Ext = flexion / extension; Abd/Add = abduction / adduction
The poor ICC and NI were highlighted in light gray and the SEM >6.2° was highlighted in dark gray