Chapter 2

Evaluation of clinical spasticity assessment in cerebral palsy using inertial sensors

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2.1 Abstract

Spasticity is clinically assessed using goniometry to measure the joint angle of the catch (AOC) during fast passive muscle stretch. The precision and accuracy of the goniometric AOC measurements is questionable, due to inevitable joint repositioning after occurrence of the catch. This study aims to evaluate the use of goniometry in estimating the AOC in spasticity assessment of the medial hamstrings, soleus and gastrocnemius in twenty children with cerebral palsy (CP). An inertial and magnetic measurement system (IMMS) was used as a reference. The sensors of the IMMS were initially validated with an optoelectronic marker system to measure 3D orientation. They were proved to be accurate within 1°. To evaluate the precision and accuracy of the goniometry, the joint angle measured with the goniometer after repositioning was compared with the joint angle measured simultaneously with the IMMS. The goniometry joint angle was also compared with the true AOC, detected and measured with the IMMS during the fast muscle stretch. Results showed that goniometry is an imprecise method to measure the true AOC in spasticity assessment. The error is mainly due to joint repositioning after the fast muscle stretch. For spasticity assessment, it is advised to apply the IMMS when a precise measurement of the angle of catch is required.

2.2 Introduction

Cerebral palsy (CP) is the most common motor disability in childhood, characterised by a persistent disorder of posture or movement due to a non-progressive disorder of the immature brain [1]. Spastic paresis is the most common type of CP, affecting motor ability. Clinical assessment of spasticity is important in children with CP, not only to diagnose spasticity, but also to support clinical decision-making and to evaluate the effect of treatment. To distinguish spasticity from other impaired muscle functions, a robust definition of spasticity, an unambiguous test protocol, and reliable instruments are crucial. The most commonly used definition of spasticity was described by Lance (1980): *"a motor disorder characterized by a velocity dependent increase in tonic stretch reflexes (muscle tone) with exaggerated tendon jerks, resulting from hyper excitability of the stretch reflex, as one component of the upper motor neurone syndrome"* [2].

Different clinical scales have been developed and used to assess spasticity during physical examination, such as the (Modified) Ashworth scale [3], the (Modified) Tardieu Scale (TS) [4], the Pendulum test [5] and the Spasticity Test (SPAT) [6]. Only the TS and the SPAT (a simplification of the TS) are based on Lance's definition. In these tests, the range of motion (ROM) is assessed by slow passive stretch of the muscle of interest. Subsequently, a fast passive stretch of the muscle is performed to detect a 'catch'. The catch is defined as: *"a sudden appearance of increased muscle activity in response to the fast passive stretch, which leads to an abrupt stop or increased resistance during the joint movement, at a certain angle (AOC: the angle of catch) before the end ROM is reached"* [7,8]. In literature and clinical practice the catch is accepted to be the dominant phenomenon of spasticity [6-9]. Boyd and Graham [4] described that the dynamic component (i.e. the difference between ROM and AOC) can be used for treatment decisions of spasticity.

The AOC is usually measured using goniometry. To assess the AOC, the examiner has to reposition the joint *after* the fast muscle stretch, in the position where the catch occurred [4,6]. A second examiner then uses a goniometer to measure the joint angle. Precision and accuracy of goniometric measurements of joint angles have been questioned [10,11]. Repositioning and goniometry may introduce errors that affect precision and accuracy of the AOC estimation.

Accurate measurement of the AOC during the fast passive muscle stretch could be performed using an optoelectronic marker system (OMS). However, during physical examination, markers are easily hidden from sight. An alternative is the use of lightweight

sensors of an inertial and magnetic measurement system (IMMS), containing tri-axial accelerometers, gyroscopes and magnetic sensors, developed for ambulatory measurements of 3D orientation of human body segments [12-19]. In comparison to OMS, the first generation IMMS are reported to be accurate within 3^{o} RMSE [12,13,19]. The sensors appear to be adequate for the accurate measurement of fast rotation.
The aims of the present study were: (i) to technically validate the IMMS for measuring 3D orientation during spasticity assessment; and (ii) to evaluate the precision and accuracy of goniometry to estimate the AOC during fast muscle stretch, in the assessment of spasticity in children with CP, using IMMS as a reference system to obtain joint angles. We hypothesized that IMMS are valid to measure 3D orientation and can be used for estimation of the AOC. Secondly, we hypothesized that goniometry is an imprecise and inaccurate method to measure the AOC, mainly due to incorrect repositioning of the joint.

2.3 Methods

2.3.1 Subjects

One healthy subject (26 years; body mass 50 kg; body height 150cm) participated in the validation study. The goniometry study included twenty children with spastic CP (5-14 years; body mass 35±14 kg (mean ± standard deviation); body height 139±19 cm; GMFCS range I-IV [20]). The Medical Ethics Committee of the VU University Medical Center, Amsterdam (the Netherlands), approved the study. Full written informed consent was obtained from all parents and children aged 12 years and older.

2.3.2 Procedure

In both studies, fast passive muscle stretches of the medial hamstrings, soleus and gastrocnemius muscles, according to the test protocol of the SPAT [6], were undertaken by an experienced examiner, starting from standardised joint positions (Table 2.1). In the validation study, the right leg was tested. In the goniometry study, the affected (hemiplegia), the most affected (asymmetrical diplegia) or the right leg (symmetrical diplegia) was tested. All muscles were tested three times.
Two sensor units of the IMMS (MT9, Xsens Technologies, Enschede, the Netherlands) tracked the motion of the proximal and distal segments during the tests (Figure 2.1 and Table 2.1), with a sample frequency of 100 Hz. Each sensor was attached securely to the

segment, using neoprene straps, to prevent change of orientation of the sensor with respect to the segment. All tests were performed on a couch with a wooden frame, to avoid magnetic disturbances in the magnetometers of the IMMS. Prior to the actual tests, a measurement was performed in reference posture for calibration purposes (Table 2.1).
In the validation study, a cluster of three markers of an OMS (Optotrak 3020; Northern Digital Inc., Waterloo, Ontario, Canada) was placed on each IMMS sensor, to track its 3D orientation, with a sample frequency of 100 Hz. Data of the IMMS and the OMS were post-hoc synchronized using cross-correlation [21].
In the goniometry study, the experienced examiner performed the fast muscle stretch, and repositioned the joint in the position where the catch first appeared (the encountered AOC). Subsequently, a second experienced examiner used goniometry to measure the joint angle. For the medial hamstrings test, the knee angle was measured using the Gollehon Extendable Goniometer (Lafayette Instrument Company, IN 47903, USA). For the soleus and the gastrocnemius tests, the ankle angle was measured with the Biplane Goniometer (Lafayette Instrument Company, IN 47903, USA). To aid correct placement of the goniometer, bony landmarks were marked. To compare the goniometry with the IMMS, the moment of goniometric readout was marked in the IMMS signals, using a footswitch signal.

2.3.3 Data analysis

2.3.3.1 Validation study

To validate the IMMS, nine trials of joint motion (three for each muscle), were analysed. To determine the difference of the IMMS with respect to the OMS, the mean root mean square error (RMSE) in 3D orientation angles, averaged for the three trials of each muscle, was used. An RMSE less then 3^{o} was considered to be acceptable. For comparison purposes, the 3D orientation of the IMMS, expressed in its own global coordinate system, defined by the local magnetic north and the gravity, was transformed into 3D orientation in the global coordinate system of the OMS. Orientation angles (x,y,z-Euler angles) of the IMMS sensors and the OMS markers were then obtained from decomposition of 3D orientation.

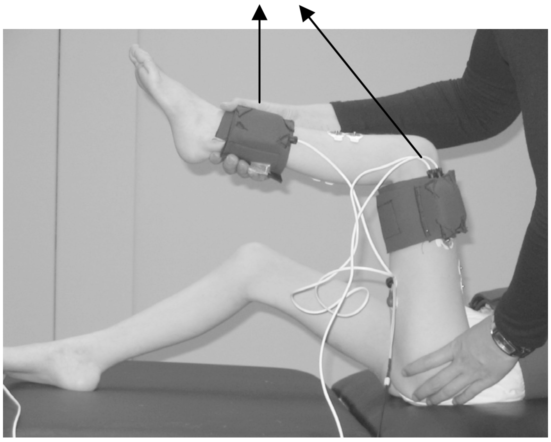

Figure 2.1. Setup of the spasticity assessment test of the hamstrings in a child with cerebral palsy. The knee joint is positioned in reference position. Two sensors of the inertial and magnetic measurement system (IMMS) are embedded in neoprene straps on the proximal and distal segment. Goniometry is not shown in the picture.

Table 2.1. The Spasticity Test

SPAT			
	Hamstrings	**Soleus**	**Gastrocnemius**
Joint	Knee	Ankle	Ankle
Segment			
Proximal	Thigh	Shank	Shank
Distal	Shank	Foot	Foot
Patient position			
Supine/prone	Supine	Supine	Supine
Hip	90^{o} flexion	90^{o} flexion	Extension
Knee	Maximal flexion	90^{o} flexion	Extension
Ankle	Not relevant	Maximal plantar flexion	Maximal plantar flexion
Joint motion	Knee extension	Ankle dorsi flexion	Ankle dorsi flexion
Joint angle of catch			
Name	(Popliteal) Knee angle	Ankle angle	Ankle angle
Reference	Full extension is 0^{o}	0^{o} dorsi/plantar	0^{o} dorsi/plantar
Reference position			
Supine/prone	Supine	Supine	Supine
Hip	90^{o} flexion	90^{o} flexion	90^{o} flexion
Knee	90^{o} flexion	90^{o} flexion	90^{o} flexion
Ankle	Not relevant	0^{o}	0^{o}

2.3.3.2 Goniometry study

To compare the goniometric measurement of the AOC with the IMMS, the units of measurement of goniometry and IMMS had to be identical. Therefore, the 3D orientations of the IMMS were translated into a two dimensional joint angle (knee and ankle flexion-extension). For this translation procedure, the relation between sensor (technical frame) and segment (anatomical frame) had to be determined, in order to allow the sensor to estimate body segment motions [18]. To estimate the anatomical frames of the segments with respect to the technical frames of the IMMS, the helical rotation axis [22,23] during the joint motion was determined (i.e. the flexion-extension axis, Table 2.1). This axis was obtained from the proximal and distal sensor orientations during the muscle stretch. Using the reference position, a second anatomical axis of each segment was obtained and, subsequently, the segment orientation with respect to the sensor orientation could be reconstructed. This was used to estimate the orientation of the proximal and distal body segments during the muscle stretch. Subsequently, the joint orientation was calculated, i.e. the distal segment orientation with respect to the proximal segment orientation. Finally, the joint angle around the joint rotation axis was obtained by decomposing the joint orientation. The joint angle was expressed with respect to the reference position.

Two different IMMS joint angles for the AOC could be derived: (i) the AOC measured simultaneously with the goniometry (*after* joint repositioning), as marked by the footswitch signal (IMMS-REPOS); and (ii) the AOC measured with the IMMS *during* the fast passive stretch (IMMS-AOC), for which the angle of maximal joint angular deceleration was calculated. Based on the definition of the catch [8], this is the true AOC. To estimate IMMS-AOC, joint angular acceleration was obtained by double differentiation of the joint angle, and bidirectional first-order low-pass filtered at 10 Hz.

Subsequently, to estimate the precision and accuracy of goniometry with respect to the IMMS, three measurement outcomes were used and compared to each other: (i) the AOC measured after repositioning with the goniometer (GONIO); (ii) the same angle measured with the sensors of the IMMS (IMMS-REPOS); and (iii) the actual AOC, detected with the IMMS (IMMS-AOC). GONIO versus IMMS-AOC represented the total error of goniometry. Two sources of error could be separated: the error due to the measurements system: GONIO versus IMMS-REPOS; and the error due to joint repositioning: IMMS-REPOS versus IMMS-AOC.

For all three outcome comparisons, Pearson R correlation coefficients were calculated, for each tested muscle. Correlations were considered to be good for $R>0.75$. Precision was defined as the absolute difference between the measured joint angles. The mean absolute difference and standard deviation, and the maximum absolute difference per muscle were calculated. The paired sample t-test was used to estimate whether the differences were significant. Accuracy was defined as the mean difference between the measured joint angles. The paired sample t-test was used to investigate whether differences were systematic. Statistical significance was accepted for $P<0.05$.

2.4 Results

2.4.1 Validation of the IMMS

Mean RMSE (IMMS versus OMS) of the proximal thigh sensor, the distal shank sensor, and the distal sensor with respect to the proximal sensor during knee joint motion (to assess the hamstrings muscle) were 0.5 ± 0.4^{o}, 0.5 ± 0.3^{o} and 0.2 ± 0.1^{o} respectively. Mean RMSE of the proximal shank sensor, the distal foot sensor, and the distal sensor with respect to the proximal sensor during ankle joint motion (to assess the soleus and gastrocnemius muscle) were 0.4 ± 0.3^{o}, 1.6 ± 1.0^{o} and 0.6 ± 0.5^{o} respectively.

2.4.2 Evaluation of AOC goniometry

Figure 2.2 shows an example of the hamstrings test in a child with spastic CP. The true AOC (i.e. IMMS-AOC) is 105^{o} (marked in the figure by the asterisk). The example illustrates that the AOC was indeed an abrupt stop of the joint movement before the end ROM (67^{o}) was reached [7,8]. Goniometry (i.e. GONIO and IMMS-REPOS, marked by the square) was performed *after* repositioning of the joint towards the angle of the encountered catch.

Figure 2.3 presents the measured joint angles of (I) GONIO versus IMMS-AOC, (II) GONIO versus IMMS-REPOS and (III) IMMS-REPOS versus IMMS-AOC. Some trials had to be excluded from analyses, because of movement during the reference position or absence of a footswitch signal (six of the hamstrings test, sixteen of the soleus test, and sixteen of gastrocnemius test). For IMMS-AOC, trials in which no clear catch was estimated were excluded. The lines in Figure 2.3 are the identity lines, i.e. x-values are identical to y-values. Table 2.2 presents the Pearson correlation coefficients, the absolute differences and the mean differences of I, II and III. The mean difference reflects whether a difference

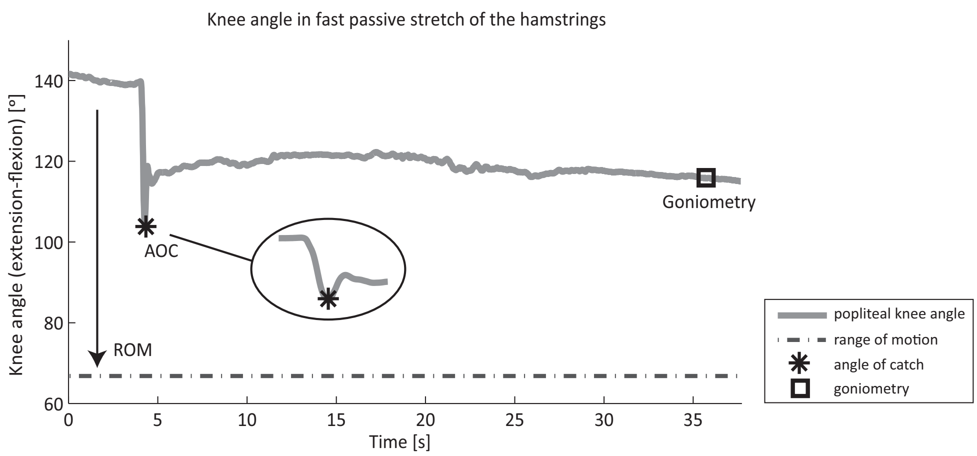

Figure 2.2. Example of knee angle (popliteal angle) in fast passive stretch test of the hamstrings muscle measured with the inertial and magnetic measurement system (IMMS). Solid line: knee angle; dot-dashed line: end range of motion (ROM); Asterisk: IMMS-AOC (true angle of catch (AOC)); Square: IMMS-REPOS and GONIO (timing of goniometry was marked in the IMMS signal using a footswitch)

is systematic: a positive difference means that the joint angles expressed along the x-axis of the graphs in Figure 2.3 are over-estimated with respect to the joint angles expressed on the y-axis.

Overall, the correlations of GONIO versus IMMS-AOC (I) were low (R<0.75). Absolute differences were high (maximal 28^o), and all significant. The gastrocnemius test showed a significant mean difference, which suggests that the AOC was systematically over-estimated (i.e. less plantar flexion) when the goniometer was used. Standard deviations of the mean differences were high. The correlations of GONIO versus IMMS-REPOS (II) were high for the hamstrings and the soleus tests. Absolute differences were relatively low in comparison to (I), but showed high individual differences (maximal 16^o), and were significant for all muscles. The mean differences showed no significant systematic difference in the measured joint angle. The correlations of IMMS-REPOS versus IMMS-AOC (III) were only high for the soleus test. Absolute differences were all significant and especially for the hamstrings high (maximal 27^o). The ankle angle in the gastrocnemius test showed a significant mean difference, which suggests that, after repositioning, the AOC was systematically over-estimated (i.e. less plantar flexion).

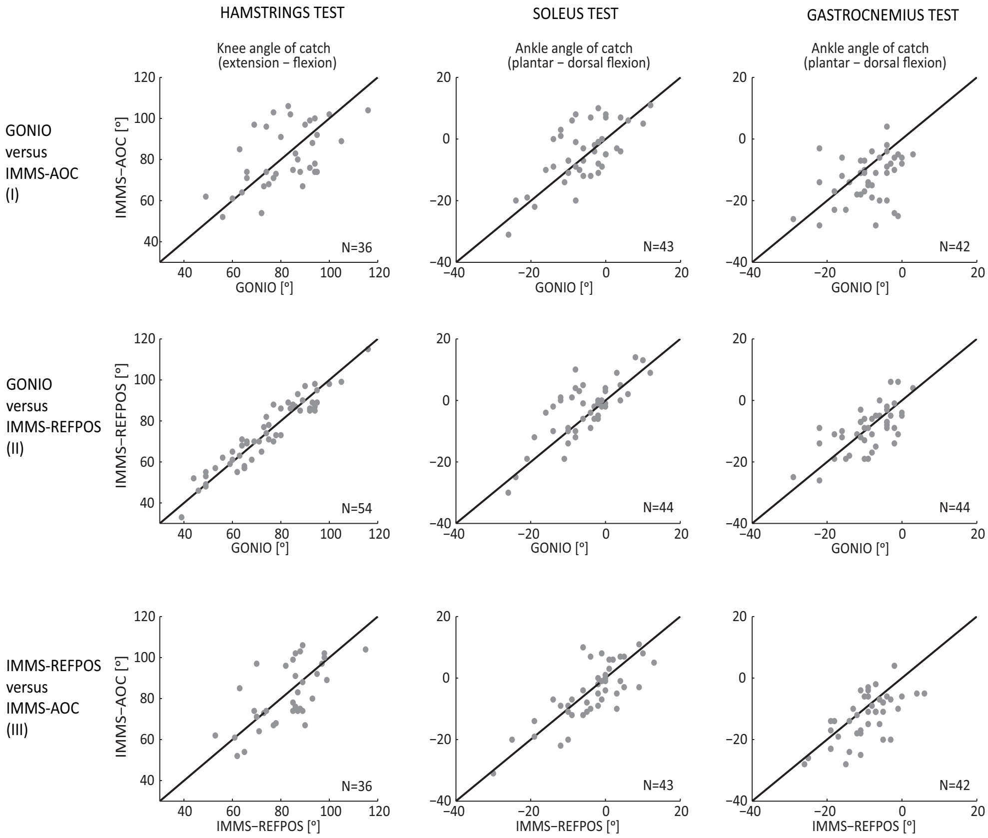

Figure 2.3. Angle of catch (AOC) of the hamstrings, soleus and gastrocnemius tests. Three different measured AOCs compared to each other (blue dots): (I) GONIO versus IMMS-AOC (true AOC using IMMS), (II) GONIO versus IMMS-REPOS (IMMS synchronously to goniometry), and (III) IMMS-REPOS versus IMMS-AOC. Black line: identity (x=y).

2.5 Discussion

2.5.1 Validation of inertial sensors

IMMS were valid to measure 3D orientation of body segments during fast passive muscle stretch. The RMSE of the IMMS with respect to the OMS was low (about 1^{o}).

Table 2.2. Comparison of measured joint angles of catch

Angle of catch		muscle	N	correlation	difference				
				Pearson R		*mean±SD (max) [°]*	*SE*	*95% CI*	*P*
(I)	**GONIO versus IMMS-AOC**	*HAM*	36	0.56	*abs.*	10±7.6 (28)	1.3	7.8-12.9	< 0.001 *
					mn.	0.9±13	2.2	-3.5-5.3	0.693
		SOL	43	0.70	*abs.*	5.3±4.2 (16)	0.7	4.0-6.6	< 0.001 *
					mn.	-0.8±6.4	1.0	-2.9-1.3	0.463
		GAS	42	0.43	*abs.*	6.7±5.6 (24)	0.9	5.0-8.4	< 0.001 *
					mn.	3.0±8.2	1.3	0.5-5.6	0.022 *
(II)	**GONIO versus IMMS-REPOS**	*HAM*	54	0.95	*abs.*	4.4±2.7 (9)	0.4	3.6-5.1	< 0.001 *
					mn.	0.3±5.2	0.7	-1.1-1.7	0.695
		SOL	44	0.84	*abs.*	3.9±3.6 (16)	0.5	2.8-5.0	< 0.001 *
					mn.	-1.6±5.1	0.8	-3.1-0.0	0.047 *
		GAS	44	0.71	*abs.*	4.3±3.2 (13)	0.5	3.3-5.2	< 0.001 *
					mn.	-0.5±5.4	0.8	-2.2-1.1	0.521
(III)	**IMMS-REPOS versus IMMS-AOC**	*HAM*	36	0.65	*abs.*	8.3±7.1 (27)	1.2	5.9-11	< 0.001 *
					mn.	1.3±11	1.8	-2.4-4.9	0.496
		SOL	43	0.75	*abs.*	4.8±4.2 (16)	0.6	3.5-6.0	< 0.001 *
					mn.	0.7±6.4	1.0	-1.3-2.7	0.477
		GAS	42	0.71	*abs.*	5.2±4.0 (15)	0.6	4.0-6.5	< 0.001 *
					mn.	3.1±5.9	0.9	1.3-5.0	0.001 *

** P<0.05*
HAM = hamstrings; SOL = soleus; GAS = gastrocnemius
N = total number of included tests; SD = standard deviation
SE = standard error mean; CI = confidence interval
abs. = absolute difference; mn. = mean difference
GONIO = the joint angle measured after repositioning with goniometry
IMMS-REPOS = the joint angle measured after repositioning with the sensors of the IMMS
IMMS-AOC = the actual angle of catch, detected with the IMMS during the test

This proved high precision of the gyroscopes for this type of measurement, and no effect of possible magnetic disturbances during the tests, which could have influenced the orientation estimation [12]. Although the technical validation of the IMMS was performed on a healthy subject, results can be generalized to children with CP. An identical protocol and setup was used. Therefore, we conclude that the sensors of the IMMS are valid to measure 3D orientation of segments during spasticity assessment in children with CP.

2.5.2 Evaluation of AOC goniometry

An incorrectly estimated AOC could be critical in spasticity assessment of muscles. For clinical decision-making and evaluation of treatment, accurate physical examination is, at least, as important as clinical gait analysis. In gait analysis, most studies providing estimates of data error reported values (standard deviations or standard error) of less then 5^{o} [24,25]. In contrast, our study found higher standard deviations of the mean differences and considerable absolute differences between goniometry (GONIO) and the true angle of catch as measured with the IMMS (IMMS-AOC). These errors may be explained by differences between the measurement systems and the repositioning of the joint.

Differences in measurement systems (II: GONIO versus IMMS-REPOS) may be explained by (i) miscalculation of the joint angles with the IMMS using the helical axis method, (ii) use of an erroneous reference position for the IMMS, or (iii) malalignment of the goniometer with respect to the joint, or, in some cases, erroneous readout of the goniometer.

First, 3D orientation estimation of the IMMS is accurate, although the actual joint angle depends on correct estimation of the helical rotation axis and on the reference position measurement. Slight deviation of the rotation axis could occur, since joint motion was not always performed purely around the flexion-extension axis of the joint, especially at the ankle. We assume this affected the estimation of the actual joint angle only minimally, since the mean of the rotation axes in time was used to determine the actual rotation axis of the joint. Secondly, we are confident that the joint angle obtained from the IMMS was correctly expressed with respect to the reference position, since bony landmarks were used to position the joint in a standardized reference position. Thirdly, to minimize errors due to malalignment of the goniometer, a standardized protocol and marked bony landmarks for the goniometry were used. However, reliability of goniometry in clinical decision-making has been questioned [10,11,26], with reported errors up to 10^{o} for the ankle angle and poor inter-observer reliability for the popliteal angle. The non-significant mean difference in GONIO versus IMMS-REPOS (II) indicates that goniometry is, on average, useful to measure a correct joint angle. However, goniometry malalignment could be the cause of high individual errors we encountered (up to 16^{o}).

The high absolute difference in IMMS-REPOS versus IMMS-AOC (III) shows that the main cause of incorrect AOC measurement using goniometry is repositioning of the joint. The examiner was not able to reposition the body segment in exactly the position where the catch appeared. The AOC of the gastrocnemius was systematically over-estimated, as reflected by the significant mean difference. Repositioning decreases the precision of the

AOC measurements. Therefore, goniometry, as currently used in clinical practice (with joint repositioning), is an imprecise method to measure the true AOC.

The true AOC as expressed by IMMS-AOC is determined at the moment of maximal deceleration of the joint motion, based on the definition of the catch. From a biomechanical perspective, the catch is defined as *“a transient increase in the force that opposes passive extension”* [27,28]. Our clinical definition of the catch corresponds to the sudden increase in joint torque, according to Newton’s second law. Combining the test with measurement of joint torque, with e.g. a hand-held dynamometer, would give insight in the contribution of non-reflex (intrinsic, visco-elastic and mechanical properties of a muscle influencing joint torque) versus the stretch reflex components in spasticity (increased muscle activity). Concurrent EMG recordings should prove whether the catch is indeed the consequence of sudden increase in muscle activity, in accordance to Lance’s definition [2].

Since joint repositioning is the main cause of incorrect estimation of the AOC when using goniometry, valid measurement of the AOC in clinical practise requires an instrumented test, e.g. the use of IMMS. This would improve spasticity assessment, because of the accuracy of the IMMS in measuring 3D orientation, and the ability to detect the true AOC without the imprecision of repositioning. IMMS sensors are lightweight, small and do not impede movement during the test. Joint angular information is provided throughout the movement, and can be used for stretch velocity standardization, which is essential to the concept of spasticity [2]. The application of IMMS could be extended to physical examination in different patient groups with conditions involving spasticity, such as stroke. Points of attention for the clinical use of IMMS are: the sensitivity to magnetic disturbances of the magnetometers in the sensors; an accurate and easy to perform anatomical segment calibration, including a measurement in reference position, required for correct estimation of joint angles; standardized and user-friendly protocol for the clinical application of the sensors; and online feedback to further standardize instrumented spasticity testing (e.g. stretch velocity). Before implementation in clinical practice, future studies should focus on the measured AOC in relation to the sudden increase in EMG activity, to joint torque, and to the velocity threshold of the reflex loop.

2.6 Conclusion

The IMMS is valid to measure 3D orientation of segments and joints during motion. Although goniometry is a reasonably accurate method to measure joint angles in static situations, it is not precise enough to measure the angle of catch in individual patients. This is mainly due to joint repositioning error after the fast muscle stretch. For spasticity assessment, IMMS sensors appear adequate in measuring the angle of catch.

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