A preliminary study on quality of knee strength measurements by means of Hand Held Dynamometer and Optoelectronic System

Analysis of knee forces and torques

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Abstract—**Strength measurements are popular in the clinical practice to evaluate the health status of patients and quantify the outcome of training programs. Currently a common method to measure strength is based on Hand Held Dynamometers (HHD) which is operator-dependent. Some studies were conducted on repeatability of strength measurements but they were limited to the statistical analysis of repeated measurements of force. In this work, the authors developed a methodology to study the quality of knee flexion/extension strength measurements by measuring the effective HHD position and orientation with respect to the patient. HHD positioning attitude was measured by means of an Optoelectronic System for which a marker protocol was defined ad-hoc. The approach allowed to assess quality of measurements and operator's ability by means of quantitative indices. The protocol permitted the evaluation of: angles of HHD application, angular range of motion of the knee and range of motion of the HHD. RMSE parameters allowed to quantify the inaccuracy associated to the selected indices. Results showed that the operator was not able to keep the subject's limb completely still. The force exerted by the subject was higher in knee extension and the knee range of motion was higher than expected, however the operator had more difficulties in holding the HHD in knee flexion trials. This work showed that HHD positioning should be as accurate as possible, as it plays an important role for the strength evaluation. Moreover, the operator should be properly trained and should be strong enough to counteract the force of the subject.**

Keywords: ***Strength, Quality assurance, Hand Held Dynamometer, Motion capture, Optoelectronic system.***

I. INTRODUCTION

Strength measurements are popular in the medical practice to evaluate the health status and effectiveness of training and rehabilitation programs. Actually, strength of lower limb was proved to be an effective indicator of gait and physical functions of the elderly population [1].

Briefly, measuring strength implies the evaluation of maximum force exerted in voluntary contraction of muscles or group of muscles. Numerous methods were developed and could be categorized as: (i) indirect methods, such as the measure of the time required to stand up and sit back on a chair for 10 times [2]; and (ii) direct ones which are generally considered preferable [3]. Nowadays, the most common method to measure muscle strength in a clinical context is the use of dynamometers: isokinetic dynamometers (ID) and Hand Held Dynamometers (HHD) that are both direct methods [1], [4], [5].

The ID is a complex device that allows measuring muscle force while the subject is performing a guided exercise by a system capable to keep constant the speed during the entire movement. The measurement of isokinetic muscle contraction allows drawing force-velocity curves and estimation of the maximum force that the patient exerts. The ID was proved to be reliable method with good inter- and intra-operator reliability and applicable to elderly subjects [1], [6]. On the other side, the ID is expensive, requires dedicate spaces, it is not portable and requires long preparation and measurement time [1], [6].

A simpler and inexpensive method to measure strength is based on the use of an HHD. This method consists in the use of a small and portable dynamometer manually operated by a trained clinician. The clinician applies the dynamometer to the patient on defined landmarks, and asks the patient to exert a force against the dynamometer [1], [5], [7], [8]. The HHD is inexpensive, if compared to IDs, portable, easy to use and it implies a protocol not time consuming. Moreover, modern HHDs can be electronically controlled and wireless connected to a PC for data storage and processing. Phillips *et al.* [9] used a HHD to measure the strength for upper and lower limbs in healthy subjects. They quantified the higher force exerted by men vs. women for all the examined muscle groups and concluded that HHD provides useful data that allow to identify the presence of weakness. In a study made by Laing *et al.* [10] it was observed that the use of HHD may underestimate the maximum force when experimenters cannot exert a sufficient opponent force to maintain fix the anatomical segment. This finding was more relevant for the knee extension strength and less relevant for the knee flexion. The operator dependence was also investigated by Kim and colleagues [1], assuming as a reference data collected via a ID and by comparing data acquired with the HHD fixed to a chair with those collected by an operator. The main outcomes were: (i) fixed and non-fixed methods showed good inter-rater reliability and (ii) the reliability of the fixed method was higher.

Martin *et al.* [5] comparatively examined HHD and ID by targeting lower limbs in healthy elderly people. They

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confirmed the validity, in general, of the protocol based on HHD and the increase of data spread when the force exerted by the participant assumed higher values. Similar results were shown by previous works [8], [11].

Application of HHD to the measure of strength in children with pathology was studied by Wuang *et al.* [12] for children with intellectual disabilities, and by Mahony *et al.* [13] for children with Spina Bifida. Their results were similar, indicating good intrarater reliability. Wuang *et al.* [12] reported values of intra-class correlation (ICC) ranging from 0.81 to 0.96, and Mahony *et al.* [13] reported values of ICC ranging from 0.76 to 0.83.

Anyway, lower values of ICC (0.42-0.73) were found by Verschuren *et al.* [14] that studied intertester reliability of HHD used to measure lower limb strength in children with Cerebral Palsy). They concluded that the HHD method is questionable, due to operator's experience.

From the literature review it is clear that the main issue in the use of HHDs is its poor reliability due to low operator strength and to low operator training and experience. Anyway the clinical use of HHD is common nowadays as it is a fast, inexpensive and easy to use method to assess strength of patients [1], [6].

Assuming that operator's deficiencies are the inaccurate positioning of the dynamometer and failure in keeping the limb still, the aim of the present paper is to implement a novel validation methodology in order to evaluate the errors on positioning and orientation of HHD and orientation of lower limb during knee strength measurements by means of an auxiliary optoelectronic system (OS).

II. MATERIALS AND METHODS

A. *Equipment*

In order to test quality of strength measurements, we developed a novel measurement protocol by using the following equipment.

Position was recorded by means of a Vicon MX OS (Oxford Metrics, UK) equipped with 8 IR cameras and strobes, Nexus 1.7 software, sampling frequency of 200 Hz and a calibrated volume, for the present study, of about 4 m^3. The overall inaccuracy was ~1 mm.

Force was measured by a MicroFet™ Hand Held Dynamometer (Hoggan Scientific, Salt Lake City, US). The dynamometer was set up to transfer real time data by means of wireless connection. HHD had a sampling frequency of 100 Hz, maximum load capacity of 1.3 kN, accuracy of 1% FSO. Data were collected by an *ad-hoc* LabView software and synchronized with motion capture data.

Protocol was performed at the Motion Analysis and Robotics Laboratory of Bambino Gesù Children's Hospital in Rome.

B. *Motion Capture Protocol*

To track position of the HHD, with respect to the subject, we designed an *ad-hoc* marker protocol. It was based on reflective passive markers which diameter was 10 mm.

The subject was equipped with a marker set based on the PlugInGait (PIG) protocol with the addition of markers on the internal epicondyle of the femur and of the ankle, in order to easily locate the knee and ankle joint centers and a cluster composed of three markers applied on the thigh (in correspondence of the *quadriceps femoris*) that allows optimal reconstruction of thigh anatomical markers in case they are covered.

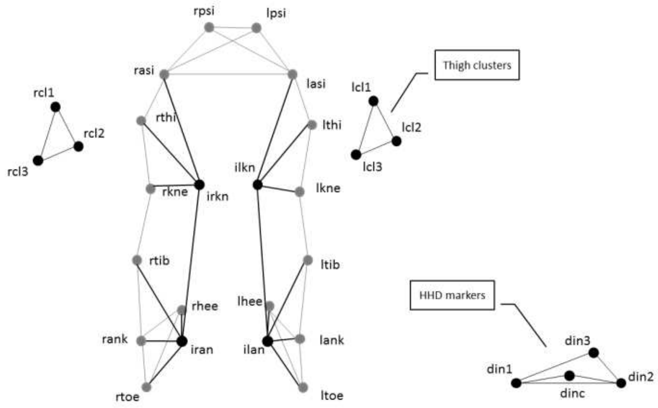

Figure. 1: Full marker protocol used for this study; grey lines and dots: PIG protocol, black dots: markers added to the PIG protocol.

Markers were applied on both sides of the body even though strength was measured only on the dominant side. Full marker protocol, including markers on the HHD, is depicted in Figure 1.

The dynamometer was equipped with four passive markers as shown in Figure 2. Markers were placed on sticks rigidly fixed to the HHD to avoid covering by the operator's hand.

The designed protocol required the acquisition of a static trial and then a set of dynamic trials. In the static trial the subject had to stand up still in the calibrated volume for about 5s. The HHD was also kept still in the calibrated volume. This allowed the recording of the position of the central marker, corresponding to the sensing surface, with respect to the other three markers. The coordinates of the central marker were reconstructed in the dynamic trials by using a 3-markers localization procedure [15]. The dynamic trials consisted in the use of the markerized HHD to measure knee strength according to the protocol described in the following.

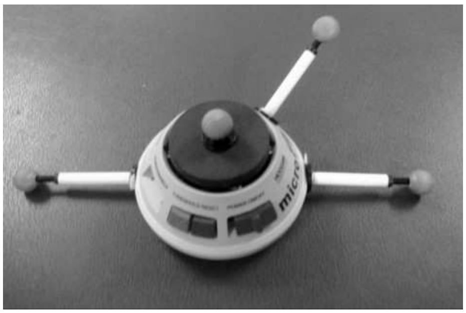

Figure 2: HHD Dynamometer equipped with passive markers.

C. *Strength measurement protocol*

The clinical protocol to measure strength of the knee flexors and knee extensors was defined in a close cooperation with the clinical partners of the neuromuscular disease group within the FP7 MD-Paedigree project.

The protocol consisted in a "make test" method that is widely accepted [5], [16]. HHD is held by a trained clinician and the trial is performed according to the following directions:

- Extension: Subject sitting, lower legs hanging from the table with hips and knees in flexion at 90°. HHD was placed proximal to the ankle on the anterior surface of the lower leg. Manual fixation at the thigh and resistance exerted by the operator at the shank in knee flexion direction.
- Flexion: Subject sitting, lower legs hanging from the table with hips and knees in flexion at 90°. HHD was placed proximal to the ankle on the posterior surface of the lower leg. Manual fixation at the thigh and resistance exerted by the operator at the shank in knee extension direction.

The operator must counteract the force of the patient trying to keep the shank still. The patient had to exert its maximum force against the HHD for about five seconds. The participants were also instructed to avoid explosive contraction but to increase force gradually to the maximum [16]. Moreover, the operator also measured the distance between the knee and the HHD application landmark by using a measuring tape.

The trials were repeated 5 times for knee extension and 5 times for knee flexion with a resting time of about 30 s between trials to avoid fatigue effects.

D. *Subjects*

Inclusion criteria were: healthy adult subjects of both sexes from 18 to 35 years old. Subjects must not have any neurological or orthopedic disorders and must not have had surgery to the lower limb joints.

All the subjects were evaluated by a trained clinician before inclusion.

Ten healthy adult subjects were enrolled in this study: 6 males, 4 females, mean age 27.3±1.4 years, mean height 169.2±11.2 cm, mean body mass 65.4±11.2 kg. They were all right handed even though this was not an inclusion criterion.

Each subject was informed and signed the consent prior to the participation.

E. *Study approval*

This study was approved by the ethical review board of Children's Hospital Bambino Gesù Rome.

F. *Trials and processing*

Data recorded for each trial were pre-processed by Vicon Nexus 1.7 software (Vicon Motion Systems, UK). Pre-processing included: track labelling, interpolation, smoothing and C3D export.

C3D data were then processed according to *ad-hoc* built MATLAB (MathWorks, USA) scripts.

A local reference system (RS) axes was defined for the shank:

- y-axis: parallel to the main axis of the shank, directed from the ankle joint to the knee joint.
- yz plane: the plane containing the y-axis and the vector from the knee center to the lateral tibial marker. z-axis is in the medio-lateral direction, pointing to the right of the subject.
- Origin: knee center.

In accordance with the previously cited references, for each trial we recorded the maximum force measured by HHD, addressed in the following as nominal force (F_{nom}), and the nominal knee moment (M_{nom}) simply obtained with the nominal lever arm.

Taking advantage of the motion capture protocol used, we also measured the following kinematic and kinetic quantities:

- Knee Range of Motion (RoM), as the angular displacement of the knee from the resting position.
- Angles between the dynamometer and the shank on the sagittal plane (A1) and on the transverse plane (A2) at the instant in which the maximum force is recorded.
- Ranges of Motion of the angles A1 and A2 (RoM-A1 and RoM-A2) during the whole trial.
- Actual knee moment (M_x, M_y, M_z), computed by knowing the actual position of the HHD and the actual direction of its sensible axis.

The main component of knee moment is on the z-axis and, ideally, lateral component should be ~0 Nm. Quality analysis of strength measurements is conducted on the moment results, as they take into account overall effects due to the positioning and orientation of HHD performed by the operator.

To quantify the difference between the nominal value of moment and the actual moment components (M_x, M_x and M_z), the root-mean-square error (RMSE) was computed. Since the nominal moment is assumed only on the z-axis, RMSEs were defined according to the following equations (expressed as % of the maximum nominal moment):

$$RMSE_z = \sqrt{\frac{\sum_{i=1}^{N}\left(M_z^i - M_{nom}^i\right)^2}{N}} * \left|\frac{100}{\max(M_{nom})}\right| \quad (1)$$

$$RMSE_x = \sqrt{\frac{\sum_{i=1}^{N}\left(M_x^i\right)^2}{N}} * \left|\frac{100}{\max(M_{nom})}\right| \quad (2)$$

$$RMSE_y = \sqrt{\frac{\sum_{i=1}^{N}\left(M_y^i\right)^2}{N}} * \left|\frac{100}{\max(M_{nom})}\right| \quad (3)$$

$$RMSE_{xy} = \sqrt{(RMSE_x)^2 + \left(RMSE_y\right)^2} \quad (4)$$

Where: N is the number of trials recorded for each subject and $\max(M_{nom})$ is the maximum value of subject's nominal moment. RMSEs were computed for each subject.

RMSEs of lateral components, that are *x* and *y,* were merged within a single parameter (eq. 4) that provide an evaluation on the magnitude of lateral components of moment that are neglected in usual clinical strength assessment.

All the parameters were averaged between the five repetitions of each subject. Coefficient of variation (CV) of each parameter, defined as the % ratio between standard deviation (SD) and mean:

$$CV\% = \left|\frac{SD}{mean}\right| * 100 \quad (5)$$

was computed to quantify repeatability within the single subject.

III. RESULTS AND DISCUSSION

The goal of the present work is the quality assessment of strength measurements by analyzing movements and inaccuracy due to the operator thanks to additional measurements gathered via a OS assumed as reference.

Uncertainties of the nominal force and the nominal moment were estimated taking into account the uncertainties of HHD and tape (1 mm) used to measure the lever arm. The uncertainty was therefore estimated as 13 N for the nominal force and 4 Nm for the nominal moment.

Table 1 shows results of kinematic and kinetic analysis of knee extension trials. Results of knee flexion trials are shown in Table 2. For each parameter is reported the mean value and SD between subjects.

TABLE I. KNEE EXTENSION

	Mean (SD)	*CV% (SD)*
Knee RoM [°]	32 (12)	20.9 (12.1)
A1[a] [°]	93 (7)	3.4 (2.0)
RoM-A1 [°]	14 (6)	27.3 (8.6)
A2[a] [°]	90 (8)	5.7 (2.1)
RoM-A2 [°]	21 (7)	27.1 (9.5)
F_nom[b] [N]	240 (29)	7.6 (2.9)
M_nom[b] [Nm]	83 (13)	7.6 (3.0)
RMSEz [%]	4.8 (1.7)	
RMSExy [%]	15.3 (7.6)	
RMSEz [Nm]	4 (2)	
RMSExy [Nm]	12 (5)	

[a] A1 is the angle on the sagittal plane, A2 is the angle on the transverse plane.

[b] F_nom is the nominal force. M_nom is the nominal moment.

TABLE II. KNEE FLEXION

	Mean (SD)	*CV% (SD)*
Knee RoM [°]	27 (5)	16.7 (7.2)
A1[a] [°]	87 (8)	9.1 (11.4)
RoM-A1 [°]	20 (14)	36.3 (14.9)
A2[a] [°]	101 (8)	4.1 (1.9)
RoM-A2 [°]	16 (6)	34.1 (17.1)
F_nom[b] [N]	-138 (22)	6.9 (1.5)
M_nom[b] [Nm]	-46 (6)	6.8 (1.6)
RMSEz [%]	11.6 (5.7)	
RMSExy [%]	20.4 (11.5)	
RMSEz [Nm]	5 (3)	
RMSExy [Nm]	9 (6)	

[a] A1 is the angle on the sagittal plane, A2 is the angle on the transverse plane.

[b] F_nom is the nominal force, M_nom is the nominal moment.

Because for the protocol the *Make* method [5], [16] was adopted for strength measurements, subject's limb should remain still across the trial, that implies a RoM ideally near to 0°. In our analysis, the measured angular RoM was never equal to 0° and we observed a value of 32±12° across the subjects; hence, the operator was not able to hold the limb completely still. This fact affected the strength measurement, as the operator was not able to exert a correct opposing force to the subject. This result is coherent with the results of Kim *et al.* [1] that proved a better measurement validity when the HHD is fixed with Velcro fixation than it is held by the operator.

From the results, we observed that Knee RoM had more variability in the knee extension trials than knee flexion, in terms of both mean value and CV. This finding can be related to the lower force exerted in flexion trials and it was in agreement with the results of Laing *et al.*[10].

Repeatability of measurements was quantified for each subject by means of the CV% of the force and moment. The average CV% was low (< 10%) for both knee extension and knee flexion trials, meaning high repeatability of measurements, coherently with previous studies [1], [5], [9].

Positioning angles A1 and A2 were close to 90° with a low CV % (<10%) , meaning a good positioning of the HHD on the shank. Worst results were obtained for the knee flexion trials, due to the operator's position that had to extend his arm behind the shank and therefore had a poor control of positioning.

Ranges of motion of angles A1 and A2 quantified the stability of the operator's hand across the trial. They were in the range of 20° with high CV%, >25% for knee extension and >30% for knee flexion, meaning instability and movement of the HHD during the trial. This finding confirmed the operator's dependence of the measurement quality [1], [5], [8], [17] and also confirmed the poor control of HHD positioning in knee flex trials.

In a clinical context, only nominal force and moment are measured and they are assumed as the force and moment on the axis of flex/extension while lateral components are neglected. RMSE parameters were therefore computed in order to quantify the inaccuracy committed by neglecting the lateral components. More precisely, RMSE_z represented the error between the nominal moment and the component of the actual moment on the z-axis that is the flex/ext axis, while RMSE_{xy} represented the magnitude of lateral components of the actual moment.

The knee extension trials had a RMSE_z <5% indicating a low error, while RMSE_z for flexion was >10%. Also RMSE_{xy}, that represents the effect of lateral components of moment, was higher for knee flexion (20.4%) than knee extension (15.3%).

Absolute RMSEs on the main axis were comparable with the respective uncertainty level. RMSEs of lateral components were slightly higher but lower than the moment on the main axis. These findings were connected to the angular displacement observed in A1 and A2 values and confirmed that angular misplacement induced an inaccuracy in the estimation of flex/extension moment.

IV. CONCLUSION

In this work a novel methodology to estimate the quality of strength measurements, taking into account movements of HHD and of patient's lower limb due to the operator's dexterity, was proposed.

Quantitative results here reported were in agreement with the results of previous studies on HHD reliability. The force and moment exerted by the subjects were higher in knee extension trials with respect to knee flexion trials. Knee flexion trials had some issues due to HHD positioning. These issues were represented by angles A1 and A2 and their ranges of motion. Moreover, the operator was not able to keep the limb of the subject perfectly still.

This work confirmed that specific attention has to be paid for HHD positioning in knee flexion and extension trials. Stability of HHD is crucial and therefore training of the operator is extremely important. Moreover, the operator should be strong enough to exert a force equal to the force produced by the subject and avoid motion of the limb.

RMSEs values quantified the error in the estimation of knee moment due to a not-correct orientation of HHD. The RMSEs values on the main axis were small and comparable with the uncertainty levels confirming a small difference between the nominal moment and the actual moment on the main direction, therefore HHD strength assessment of knee extension and flexion could be considered reliable. Our results showed that the inaccuracy was higher in the case of knee flexion. Moreover, the RMSEs values on the lateral components indicated the presence of knee solicitation in the undesired directions therefore the operator should pay special attention in HHD positioning while assessing knee flex/ext strength.

The here-proposed methodology will be useful for the estimation of inter operator reliability and for the validation of the strength measurement protocol with subjects with neurological diseases.

The main limitation of this study is the use of a one-component dynamometer. A multi-component load cell placed in series to HHD should be used useful to better evaluate the effect of lateral components of force and moment.

REFERENCES

[1] W. K. Kim, D. K. Kim, K. M. Seo, and S. H. Kang, “Reliability and validity of isometric knee extensor strength test with hand-held dynamometer depending on its fixation: a pilot study,” *Ann. Rehabil. Med.*, vol. 38, no. 1, pp. 84–93, Feb. 2014.

[2] M. Csuka and D. J. McCarty, “Simple method for measurement of lower extremity muscle strength,” *Am. J. Med.*, vol. 78, no. 1, pp. 77–81, 1985.

[3] C. J. Jones, E. R. Rikli, and W. C. Beam, “A 30-s chair-stand test as a measure of lower body strength in community-residing older adults,” *Res. Q. Exerc. Sport*, vol. 70, no. 2, pp. 113–119, 1999.

[4] J. C. Janssen and L. Le-Ngoc, “Intratester reliability and validity of concentric measurements using a new hand-held dynamometer.,” *Arch. Phys. Med. Rehabil.*, vol. 90, no. 9, pp. 1541–7, Sep. 2009.

[5] H. J. Martin, V. Yule, H. E. Syddall, E. M. Dennison, C. Cooper, and A. Aihie Sayer, “Is hand-held dynamometry useful for the measurement of quadriceps strength in older people? A comparison with the gold standard Biodex dynamometry,” *Gerontology*, vol. 52, no. 3, pp. 154–9, Jan. 2006.

[6] A. Hartmann, R. Knols, K. Murer, and E. D. de Bruin, “Reproducibility of an isokinetic strength-testing protocol of the knee and ankle in older adults,” *Gerontology*, vol. 55, no. 3, pp. 259–68, Jan. 2009.

[7] M. L. Fulcher, C. M. Hanna, and C. Raina Elley, “Reliability of handheld dynamometry in assessment of hip strength in adult male football players,” *J. Sci. Med. Sport*, vol. 13, no. 1, pp. 80–4, Jan. 2010.

[8] R. W. Bohannon, “Test-retest reliability of hand-held dynamometry during a single session of strength assessment,” *Phys. Ther.*, vol. 66, no. 2, pp. 206–9, Feb. 1986.

[9] B. A. Phillips, S. K. Lo, and F. L. Mastaglia, “Muscle force measured using ‘break’ testing with a hand-held myometer in normal subjects aged 20 to 69 years,” *Arch. Phys. Med. Rehabil.*, vol. 81, no. 5, pp. 653–661, May 2000.

[10] B. A. Laing, F. L. Mastaglia, S. K. Lo, and P. Zilko, “Comparative Assessment of Knee Strength Using Hand-Held Myometry and Isometric Dynamometry in Patients with Inflammatory Myopathy,” *Physiother. Theory Pract.*, vol. 11, no. 3, pp. 151–156, Jan. 1995.

[11] C. Y. Hsieh and R. B. Phillips, “Reliability of manual muscle testing with a computerized dynamometer,” *J. Manipulative Physiol. Ther.*, vol. 13, no. 2, pp. 72–82, Feb. 1990.

[12] Y. Wuang, J. Chang, M. Wang, and H. Lin, “Test–retest reliabilities of hand-held dynamometer for lower-limb muscle strength in intellectual disabilities,” *Res. Dev. Disabil.*, vol. 34, pp. 2281–2290, 2013.

[13] K. Mahony, A. Hunt, D. Daley, S. Sims, and R. Adams, “Inter-tester reliability and precision of manual muscle testing and hand-held dynamometry in lower limb muscles of children with spina bifida,” *Phys. Occup. Ther. Pediatr.*, vol. 29, no. 1, pp. 44–59, 2009.

[14] O. Verschuren, M. Ketelaar, T. Takken, M. Van Brussel, P. Helders, and J. Gorter, “Reliability of hand-held dynamometry and functional strength tests for the lower extremity in children with cerebral palsy,” *Disabil. Rehabil.*, vol. 30, no. 18, pp. 1358–1366, 2008.

[15] A. Ancillao, M. Galli, S. L. Vimercati, and G. Albertini, “An optoelectronic based approach for handwriting capture,” *Comput. Methods Programs Biomed.*, vol. 111, no. 2, pp. 357–365, Jun. 2013.

[16] C.-Y. Wang, S. L. Olson, and E. J. Protas, “Test-retest strength reliability: Hand-held dynamometry in community-dwelling elderly fallers,” *Arch. Phys. Med. Rehabil.*, vol. 83, no. 6, pp. 811–815, Jun. 2002.

[17] L. Willemse, M. A. Brehm, V. A. Scholtes, L. Jansen, H. Woudenberg-Vos, and A. J. Dallmeijer, “Reliability of isometric lower-extremity muscle strength measurements in children with cerebral palsy: implications for measurement design.,” *Phys. Ther.*, vol. 93, no. 7, pp. 935–41, Jul. 2013.