Repeatability and accuracy of a foot muscle strength dynamometer

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Running Title: toe strength dynamometer

Keywords: joint angle; joint torque; metatarsal phalangeal joint; foot muscles; clinical assessment

Word Count: 2800

ABSTRACT

Toe flexor strength is a pivotal biomechanical contributor for effecting balance and gait. However, there are limited reports that evaluate measurement accuracy and repeatability of this important attribute. Dynamometers are designed to measure force which can be used to derive joint torque if the perpendicular distance to the joint axis is known. However, an accurate and reliable measurement method to assess the ability of the toe flexor muscles to produce torque, is lacking. Here we describe a new device and method, designed to quantify the toe flexor torque developed at the metatarsal phalangeal joint. We evaluate measurement bias and the ability of the instrument to consistently measure what it is supposed to measure (Interclass Correlation Coefficient). Results suggest that our device is an accurate tool for measuring angle and torque with a small (0.10° and 0.07 Nm, respectively) bias. When tested for reliability and repeatability in measuring toe flexor torque (n = 10), our device showed high interclass correlation (ICC=0.99), small bias (-1.13 Nm) and small repeatability coefficient (CR = 3.9). We suggest mean bias and CR to be reported for future measurement methods and our protocol used as standard approach to measure maximal toe flexor torque.

Introduction

Adequate foot muscle strength is imperative for efficient performance of sport and activities of daily living [1]. When we stand, foot muscles provide the basis for upright balance, but during locomotion the foot has a dual function: it forms a rigid lever at foot-strike and push-off, and a shock-absorber during mid-support [2]. This is accomplished through the deformation of the arch, which is controlled and supported by small intrinsic (foot) and large extrinsic (leg) muscles. Although critical to locomotion, our ability to measure and evaluate foot muscle strength accurately is rather limited [3, 4].

Dynamometers are suggested to directly measure muscle force. They all rely on the assumption that (i) the external moment of force measured around the device axis represents the moment of the force produced by the muscles, and (ii) the force that produces such moment is equal to the muscle force. For semantical precision, hereon we will refer to torque – external moment of force – when referring to what a dynamometer is measuring.

Previous toe dynamometers described in the literature have had technical limitations: some rely on the tester providing resistance [5], while others allow gripping of the toes and, therefore have a greater contribution from the extrinsic toe flexors [6]. An alternative is a fixed dynamometer whereby participants press their toes against a fixed sensor plate (i.e. force sensors) [7, 8]. In this way, Endo, Ashton-Miller [9] used the signal from a force plate to quantify toe flexor torque around the metatarsophalangeal joint (MPJ); however, the movement was not isolated: the contribution of the moment generated among the other (bigger) joints was not accounted for. Goldmann and Brüggemann [10] introduced a system of Velcro® straps to fix the forefoot, midfoot, and rearfoot to the dynamometer while keeping the body into a standardized position. Although giving repeatable measurements, their device was not tested for accuracy and reliability. Based on the device built by Goldmann and Brüggemann [10], we developed a custom-made toe dynamometer addressing the technical limitations of previous studies while ensuring accurate measurements of torque produced by toe flexor muscles. The purpose of the present study was: 1) to assess the accuracy between the known measures for angle and torque measured by the novel dynamometer device; and 2) to assess the device re-test repeatability of maximal isometric contractions of toe flexor muscles.

Methods

In this study, we quantified the moment of force generated by toe flexor muscles around the axis of the dynamometer during maximal isometric contraction. Our design addressed two important issues when assessing toe muscle strength: angular orientation of the metatarsal heads and foot size.

Hardware and software

The device is an improved version of a previously proposed machine [10] to which we added flexibility, and adaptability. It has been designed to allow measurements to be taken in either a seated or standing position. For operation in the seated position, a knee-thigh clamping mechanism is included, with both vertical and longitudinal adjustment features (Figure 1a). The device can be set in a locked angular position to monitor a subject's ability to apply static torque, or can be set to allow free angular range of motion with adjustable mechanical limits. The height of the transverse axis of the MPJ is a function of foot size; therefore, we secured the plate on three adjustable screws with fixed rulers such that the plate position can be recorded and readjusted according to the participant's foot size. The angular orientation of the metatarsal heads also needed to be taken into consideration [11, 12]. We designed a plate with a matrix of holes to which locking pins and straps can be tethered for strapping the subject's foot into different orientations. A requirement to provide the capacity to impose and resist up to 50 Nm of torque has been met with the use of dumbbell weights loaded on to a carrier (Figure 1b), and a pulley arrangement (Figure 1c).

****** insert Figure 1 about here ******

The tension [tp] in the primary strap is the weight of the mass load. The tension in the secondary strap [ts] is equivalent to the tension in the primary strap multiplied by the ratio of the primary [rp] and secondary [rs] pulley radii. The torque [T] imposed on the phalanges shaft is the product of the secondary strap tension and the driven pulley radius [rd]. The effective radius of each pulley is the sum of the radius of the pulley surface and half the thickness of the tension strap. The primary pulley effective radius was 0.100 m, the secondary pulley radius was 0.049 m, and the driven pulley radius rd was 0.100m; therefore:

$$T[Nm] = m[Kg] * g * (rp/rs) * rd \qquad (1)$$

$$T = m * 9.81 * (.100/.049) * .100$$

$$T = m * 2.002$$

The phalanges rotation shaft carries an absolute angle rotary encoder (Figure 2a) on its end, which produces an analogue output voltage signal. The shaft assembly also includes a torsion strain cylinder element (Figure 2b), which is connected to the assembly in such a way as to ensure that the link transmits torque without being exposed to any bending, tensile or compressive loads. The main foot and phalanges resting surface plates are designed and built to provide a large range of height adjustment so that any subject's proximal phalanges centre of rotation can be aligned with the device's rotation shaft. This allows simulation of a tilted MPJ mediolateral axis of rotation, through adjustment of jacking screws accordingly on both the main foot and phalanges tooling plates. The tarsal resting surface plate includes a matrix of holes to which locking pins and straps can be tethered for strapping the subject's foot into position. Both the main foot and phalanges resting plates include millimetre linear scales for foot positioning reference (Figure 2c).

****** insert Figure 2 about here ******

The electronic instrumentation comprises two transducers, their associated signal conditioning circuitry, and a custom Labview data acquisition system running on a laptop PC and employing an NI-6009 14-bit USB DAQ module to sample the 2 analogue quantities. An absolute angle encoder (US Digital MA3 with analogue output) is directly coupled to the shaft end of the toe plate and thus directly monitors the -20 to +50 degrees' angular range of the toe plate. This transducer has a resolution of 10 bits which equates to 0.33 degrees measurement resolution.

A torque transducer and its associated amplifier monitors the torque applied by the toes to the toe plate. It covers a torque range of 0-50 Nm. The transducer was constructed in-house using a Micro-Measurements CEA-06-250US-350 full bridge strain gauge bonded to a custom designed hollow shaft and rated for 50 Nm full load. The associated strain gauge amplifier has a gain of 500 to provide an output voltage of approx. 4V at 50 Nm. Custom Labview code (National Instruments) samples the above

2 analogue channels at 100 Hz and applies the appropriate scaling factors and offsets to produce actual torque and angle values which are displayed in real-time (Figure 3a,b).

****** insert Figure 3 about here ******

Accuracy

Accuracy is intended here as the description of the systematic error (statistical bias) and random error (statistical variability) associated with a measurement [13]. In this study, limits of agreement (LoA) and mean bias were used as a measure of accuracy [14].

Angle

The predicted angle was compared to the software readings for that angle (i.e. plate fixed at 50° and record the angle). All angles from 50° dorsiflexion to 20° plantarflexion (in 10° increments) were tested. Results are reported in Table 1. For each angle, we computed the mean of 500-recorded values (10 sec).

Torque

Starting with zero weight, the weight of the carrier was added; then additional 2.5 kg calibrated weights were added. For each load, a 10 sec period was allocated before adding the next weight. The expected torque was compared to the software readings for that weight. The frontal plate was kept in a neutral position and weights were added perpendicularly to it.

Statistical analysis

For each angle, 500 values were averaged and the standard deviation calculated. The same computational process was performed for the torque. The Bland-Altman plot [14] was used to visually inspect the differences between the computed theoretical values and the measured values (of both torque and angle); and how the differences might change in proportion to the magnitude of the measure. Limits of agreement [15] were used to assess differences between two types of evaluation methods: 1) device accuracy from concurrent tests, and 2) device repeatability from the same re-test conditions. The LoA provides an estimate that 95% of measured observations can be expected to lie within limits of agreement defined by the mean bias and coefficient of repeatability. Specifically, $LoA_{between}$ = Mean difference $_{between}$ ± $CR_{between}$. For the accuracy test, the mean difference was defined by

$$\frac{\sum_{i}^{500}(x_e - x_m)}{500} \pm 95\%\ CI \qquad (2)$$

where x_e is the expected value and x_m is the measured value. The coefficient of repeatability (± $CR_{between}$) is computed by $CR_{between} = 1.96 \times SD_{between}$, where $SD_{between}$ is the standard deviation of the between method differences $(x_e - x_m)$.

Repeatability and Reliability

A study was conducted to establish the repeatability and reliability of the dynamometer in measuring the joint torques produced by the toe flexor muscles. Ten participants (7 men and 3 women, mean height 1.75 ± 0.1 m; mean weight 74.9 ± 15.5; mean BMI 24.3 ± 3.2) gave their informed consent to undergo a familiarisation and two testing sessions conducted on different (non-sequential) days.

Each participant reported to the laboratory at the same time of the day. The protocol consisted of a pre warm-up period of 1 min where the participants repeatedly performed toe flexion/extension movements with no resistance applied followed by submaximal isometric contractions with incremental exertion up to maximal contraction. After a 3-minute rest, three 5 second-maximal contractions were performed. Protocol design was such that learning effect was minimized, different ability to contract foot muscles accounted for, and maximal muscle pre-activation achieved.

Participants sat on a chair with their knee and ankle fixed at 90 degrees. Metatarsal-phalangeal joints (MPJs) were fixed at 30 degrees of dorsiflexion as recommended for optimal torque production [16] and secured to the bottom plate through a means of Velcro® straps. The head of the metatarsals (1-5) were in line with the transverse axis of the device. Raw data were filtered using a 101-point (2 sec) moving average. The highest torque value among the trials (1-3) was used for analysis.

Statistical analysis

For repeatability, mean and standard deviation of the differences between the two sessions were used to calculate the limits of agreement using the Bland-Altman plot as described previously. The coefficient of repeatability and mean bias were also computed. For reliability, a two way mixed single measures (absolute agreement) was used to calculate Interclass Correlation Coefficients (ICC; 3,1). All statistics were run in SPSS (Version 24, SPSS Inc., Chicago, IL). The level of significance was set to $\alpha=0.01$.

Results

Accuracy

Results from the accuracy study are showed in Table 1 (and appendix A). For angle, the largest difference between expected and measured values (0.23°) was at 10 degrees dorsiflexion, while the lowest error (0.03°) was recorded at 0 and 20 degrees plantarflexion. Overall, the absolute mean difference was 0.12° and the absolute percentage difference was 0.81%. For torque, the highest difference between expected and measured values (0.34 Nm) was recorded at the highest load (42.93 Nm), while the highest percentage difference (2.9%) was recorded at 7.93 Nm expected torque. Overall, the absolute average difference was 0.16 Nm with an absolute percentage difference of 0.85%. Mean bias of measurement for torque was -0.07 Nm with a CR of 0.39 Nm. For the angle, the mean bias was 0.10° with a CR of 0.21° (appendix A).

****** insert Table 1 about here ******

Repeatability and reliability

Results from the repeatability test are reported in Table 2 (and appendix A). The two testing sessions were not significantly different (t (9) = -2.11, $p = 0.64$) with a mean bias of -1.13±3.9 Nm.

The average measures interclass correlation coefficient was excellent (ICC = 0.99); with 95% of the samples having confidence intervals (CI) between 0.95 and 1.00 which shows high reliability. The within-observation variance was also found to be low (3.96 $[Nm]^2$) with a between-observation variance of 92.28 $[Nm]^2$.

****** insert Table 2 about here ******

Discussion

In this study, we tested the accuracy, repeatability and reliability of a method to test toe flexor strength. Results suggest that our bespoke dynamometer is an accurate tool for measuring angular position and torque: mean bias for torque measurements (-0.07 Nm) and for angular position measurements (0.1°) were less than a unit; the CR for torque (0.39) and for angle (0.21) were also small. Therefore, our device is not only accurate, but it has a small instrument error (noise in the measuring device).

When tested for between-session repeatability and reliability in measuring toe flexor strength, our device showed low bias (-1.13±3.9) confirming its repeatability, and high interclass correlation coefficient (ICC=0.99) confirming its reliability. Although torque measurements in the second session were generally higher than in the first, the not significant ($p = 0.41$) difference (+1.13 Nm or +6%), gives confidence on the accuracy of the number of sessions (one familiarisation and two tests) and the warm-up protocol defined, to minimizing any learning effect.

It has been reported that measurement of torque is affected by many technical factors, such as the applied methodology [17], and joint orientation [10]. Here we propose an accurate and reliable standardized methodology – with an improved design – compared with previous devices [10, 18]. The first metatarsal bone has a higher (from ground level) effective centre of rotation than the smaller toe bones, therefore the effective axis of all phalanges working together is tilted relative to the ground plane. We included an additional degree of freedom to account for the mediolateral slope of the effective rotational axis of the phalanges.

Our study is the first to propose an estimate of instrument repeatability (Limits of Agreement) when performing toe flexor strength tests by dynamometer. The importance in reporting the degree of measurement accuracy is well-documented [19-21]. Poor accuracy reduces the ability to monitor changes over time - both in clinical and experimental contexts; studies not reporting the amount of bias inherent in the measurement may over- or under-estimate the true moment of force produced, therefore their results need to be interpreted with caution.

Our device also has the potential to be used as a training tool, instead of just for evaluation. Strengthening of the foot muscles is commonly achieved with toe-flexion exercises such as towel crunches or marble pickups [22, 23], short-foot exercises that involve drawing the heads of the metatarsals toward the calcaneus without curling the toes [24], or exercises performed using exercise bands with progressive resistance [25]. However, in those exercises the extrinsic foot muscles are activated to some extent, the resistance applied is difficult to quantify exactly, and the efficiency of the training is dependent on the position held by the performer. Our device could potentially be a more effective method to reinforce foot muscles and it could simplify the training plan by setting a constant individualized position, and by setting specific resistive progression while minimizing the contribution of extrinsic foot muscles.

Although the device was accurate in measuring torque and angle, and showed a small measurement bias, it is not possible to confidently assume that the device is able to isolate toe muscles and measure only their strength. The set-up of the machine was such that muscles not crossing the MPJ should have had a small (if any) effect on torque production around that joint, however, this is not certain. It is also acknowledged that during a maximal isometric contraction the extrinsic muscles help in stabilizing the adjacent foot joints therefore, they may have an indirect role in force production. In future, concurrent use of motion capture system, electromyography, and/or foot plantar pressure devices with dynamometers will better define if any secondary movements (i.e. imperceptible heel raising) play a role in the development of torque around the MPJ.

Conclusion

This study evaluated the performance of a bespoke dynamometer, which had been designed to measure maximal toe flexor strength. The results indicate that the device is accurate when measuring torque and flexion angle, and repeatable and reliable when measuring maximal joint torque developed by toe flexor muscles. In future studies, the ability of the device to reliably discriminate between different groups of people (i.e. different gender or sport) should be tested in a larger sample.

Acknowledgement

The University's Human Research Ethics Committee (ref 24315) approved this study.

The authors report no conflicts of interest.

Funding: none.

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Figure Legends

Figure 1. Overview of the toe flexors strength device: *a* knee-thigh clamping mechanism, *b* carrier, and *c* pulley arrangement

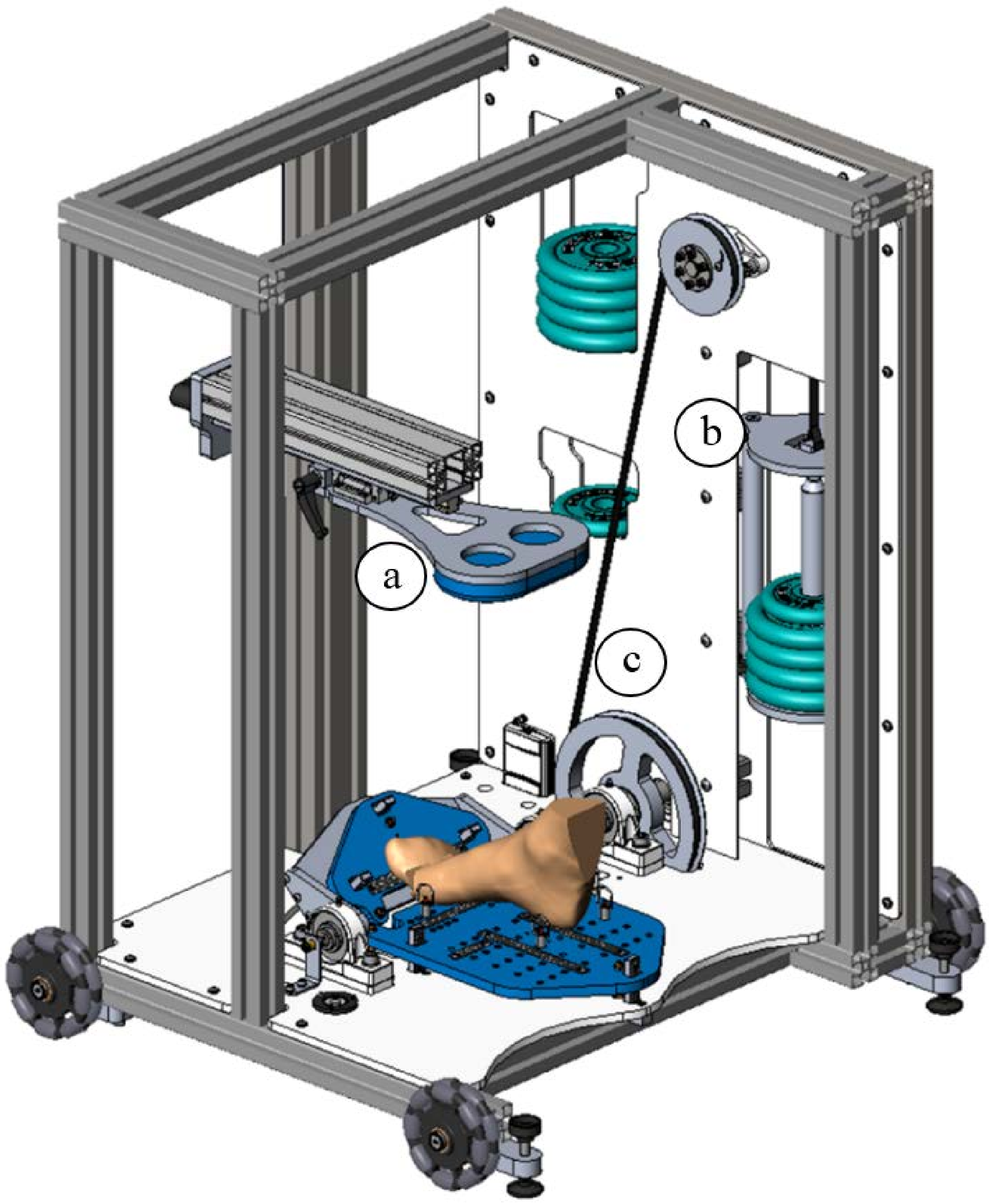

Figure 2. Schematic of the main foot and phalanges plates. *a* rotary encoder, *b* torsion strain cylinder, and *c* millimetre linear scales

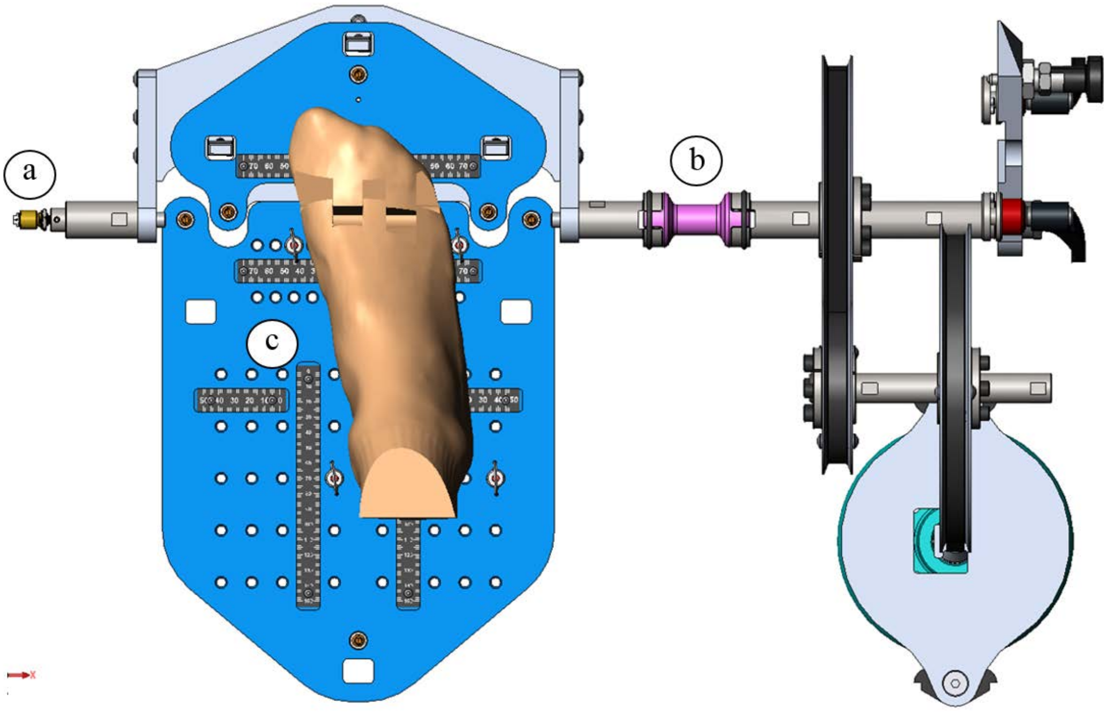

Figure 3. Labview software interface (a) and block diagram (b)

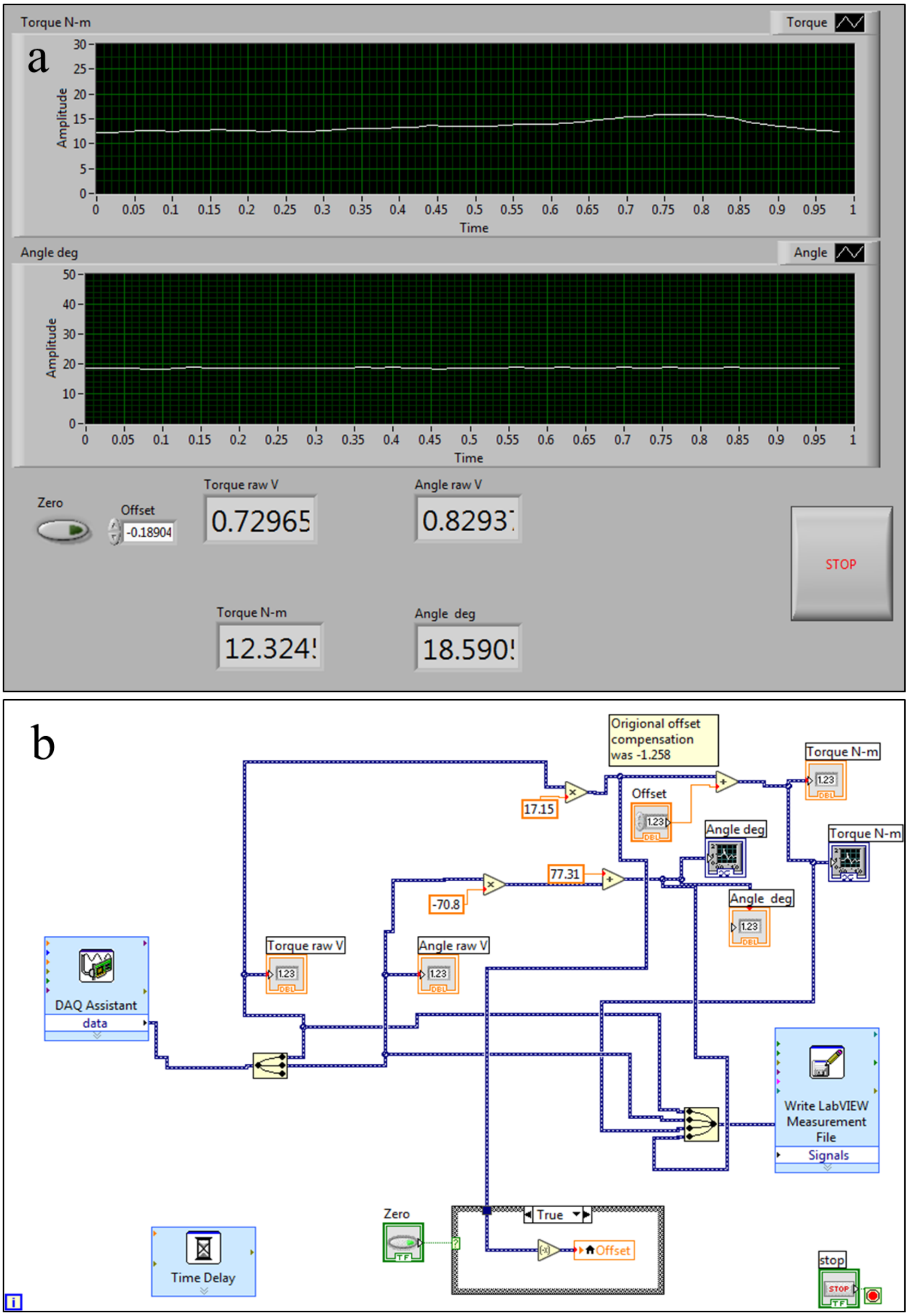

Table 1 *Accuracy results for the angle and torque measurements. Difference (Diff) between expected values and measured are reported; Absolute Average Difference (Abs Avg Diff) is also reported as raw and percentage. Mean Bias and limits of agreement (LoA) are also reported.*

Angle (°)						
Expected	Measured mean ±SD	Diff (%)	Abs Avg Diff (%)	Mean bias	LoA lower	upper
50	*49.78* ± 0.16	*-0.22 (-0.44)*	*0.12 (0.81)*	*0.10*	*-0.11*	*0.31*
40	*40.06* ± 0.17	*0.06 (0.15)*				
30	*29.91* ± 0.17	*-0.09 (-0.30)*				
20	*19.83* ± 0.16	*-0.17 (-0.85)*				
10	*9.77* ± 0.17	*0.23 (2.30)*				
0	*0.03* ± 0.16	*0.03 (-)*				
-10	*-10.15* ± 0.16	*-0.15 (-1.50)*				
-20	*-20.03* ± 0.17	*-0.03 (-0.15)*				
Torque (Nm)						
Expected	Measured mean ±SD	Diff (%)	Abs Avg Diff (%)	Mean bias	LoA lower	upper
0	*0.01* ± 0.07	*-0.01 (-)*	*0.16 (0.85)*	*-0.07*	*-0.47*	*0.32*
2.93	*2.93* ± 0.06	*0.00 (0)*				
7.93	*7.70* ± 0.07	*-0.23 (-2.90)*				
12.93	*12.76* ± 0.07	*-0.17 (-1.31)*				
17.93	*17.89* ± 0.07	*-0.04 (-0.22)*				
22.93	*22.98* ± 0.07	*0.05 (0.22)*				
27.93	*28.06* ± 0.06	*0.13 (0.47)*				
32.93	*33.24* ± 0.07	*0.31 (0.94)*				
37.93	*38.25* ± 0.06	*0.32 (0.84)*				
42.93	*43.27* ± 0.07	*0.34 (0.79)*				

Table 2 *Mean (±SD) torque produced by toe flexor muscles (in a 30° of dorsiflexion at the MPJ joint) for session one (test) and two (retest). Results reported for Interclass Correlation Coefficient (ICC), within-observation and between-observation variance [Nm]2, mean bias, and coefficient of repeatability (±CR).*

	test	retest	ICC	within	between	mean bias
	mean ±SD	mean ±SD	(95%CI)	variance	variance	(±CR)
Torque (Nm)	18.75 ± 9.2	19.88 ± 10.5	0.99 (0.95-1.00)	3.96	92.28	-1.13(±3.9)