

NOTE

Reliability and validity of the Performance Recorder 1 for measuring isometric knee flexor and extensor strength

Sarah E. Neil, MSc,¹ Alec Myring, MPT,² Mon Jef Peeters, MSc, MPT,² Ian Pirie, MPT,² Rachel Jacobs, MPT,² Michael A. Hunt, MPT, PhD,³ S. Jayne Garland, PT, PhD,⁴ and Kristin L. Campbell, PT, PhD³

¹PhD Student, School of Population and Public Health, Faculty of Medicine, University of British Columbia, Vancouver, BC, Canada

²MPT Student, Department of Physical Therapy, Faculty of Medicine, University of British Columbia, Vancouver, BC, Canada

³Assistant Professor, Department of Physical Therapy, Faculty of Medicine, University of British Columbia, Vancouver, BC, Canada

⁴Department Head, Department of Physical Therapy, Faculty of Medicine, University of British Columbia, Vancouver, BC, Canada

ABSTRACT

Background: Muscular strength is a key parameter of rehabilitation programs and a strong predictor of functional capacity. Traditional methods to measure strength, such as manual muscle testing (MMT) and hand-held dynamometry (HHD), are limited by the strength and experience of the tester. The Performance Recorder 1 (PR1) is a strength assessment tool attached to resistance training equipment and may be a time- and cost-effective tool to measure strength in clinical practice that overcomes some limitations of MMT and HHD. However, reliability and validity of the PR1 have not been reported. **Methods:** Test-retest and inter-rater reliability was assessed using the PR1 in healthy adults ($n = 15$) during isometric knee flexion and extension. Criterion-related validity was assessed through comparison of values obtained from the PR1 and Biodex® isokinetic dynamometer. **Results:** Test-retest reliability was excellent for peak knee flexion (intra-class correlation coefficient [ICC] of 0.96, 95% CI: 0.85, 0.99) and knee extension (ICC = 0.96, 95% CI: 0.87, 0.99). Inter-rater reliability was also excellent for peak knee flexion (ICC = 0.95, 95% CI: 0.85, 0.99) and peak knee extension (ICC = 0.97, 95% CI: 0.91, 0.99). Validity was moderate for peak knee flexion (ICC = 0.75, 95% CI: 0.38, 0.92) but poor for peak knee extension (ICC = 0.37, 95% CI: 0, 0.73). **Conclusions:** The PR1 provides a reliable measure of isometric knee flexor and extensor strength in healthy adults that could be used in the clinical setting, but absolute values may not be comparable to strength assessment by gold-standard measures.

INTRODUCTION

Measurement of muscular strength has important applications in both clinical practice and rehabilitation research. Muscular strength is a fundamental muscle

performance parameter that is a key determinant of physical function (Brill et al, 2000) and the ability to perform essential activities of daily living (Hasegawa et al, 2008). During a muscle contraction, the linear force produced from a single muscle or muscle group results in angular movement about the joint since the force vector does not pass through the axis of rotation. The resultant angular movement is based on the torque created by the muscle force directed at a distance from the axis of rotation. Since direct measurement of muscle force cannot be feasibly

Accepted for publication 7 February 2013

Address Correspondence to Kristin L. Campbell, PT, PhD, Assistant Professor, Department of Physical Therapy, Faculty of Medicine, University of British Columbia, Vancouver, BC, Canada. E-mail: kristin.campbell@ubc.ca

measured *in vivo*, muscular strength is most commonly reported as the torque production during a static or dynamic movement. While muscular strength can vary by a change in length of the muscle during contraction (i.e. concentric and eccentric), isometric muscle testing is the most commonly used approach, as it is simple to perform and reproduce, and effective for comparing results within a group in controlled testing conditions (Durfee and Iazzo, 2006). In addition, measurement of isometric strength has been shown to be predictive of functional capacity, especially in older adults (Salem et al, 2000), and those who have experienced functional losses due to injury (Ericsson, Roos, and Dahlberg, 2006) or disease (White et al, 2004). Therefore, a reliable method to assess isometric muscular strength is a useful clinical tool for physical therapists.

The most frequently used method of assessing muscular strength in the clinical rehabilitation setting is manual muscle testing (MMT). There is also increasing interest in the use of hand-held dynamometry (HHD). These methods are commonly used due to their simplicity in administration and cost effectiveness. The validity, test-retest reliability, and inter-tester reliability of these methods have been researched and reported (Cuthbert and Goodheart, 2007; Keating and Matyas, 1996). MMT is subjective and grading may differ between testers. Reported reliability for MMT of the lower extremities

varies from 0.63 to 0.98, with higher reliability found in more experienced clinicians (Cuthbert and Goodheart, 2007). Reported reliability of HHD for lower extremity strength ranges from 0.49 to 0.99, and is typically higher when belt stabilization is used (Bohannon et al, 2011; Kolber and Cleland, 2005; Toonstra and Mattacola, 2012). With stronger participants, both MMT and HHD are particularly imprecise, especially when measuring the lower extremities (Martin et al, 2006), as it can be difficult to stabilize the patient adequately to obtain a reliable measure (Keating and Matyas, 1996). Dynamometers such as the Biodex® dynamometer (Biodex Medical, Shirley, NY, USA), provide more reliable tests, particularly of lower extremity muscle strength, and are considered the gold standard of muscle strength measurement tools (Martin et al, 2006). The Biodex® dynamometer provides mechanically valid and reliable measures of torque, position, and velocity for both clinical and research purposes (Drouin et al, 2004) but may be prohibitively expensive for many clinical settings. A new device, the Performance Recorder 1 (PR1) (HUR Limited, Kokkola, Finland) is a small portable unit that works in conjunction with resistance training equipment to objectively measure muscular strength. The unit consists of a strain gauge that can be affixed to resistance training equipment, and a hand-held output unit, which displays force in kilograms (Figure 1). When attached

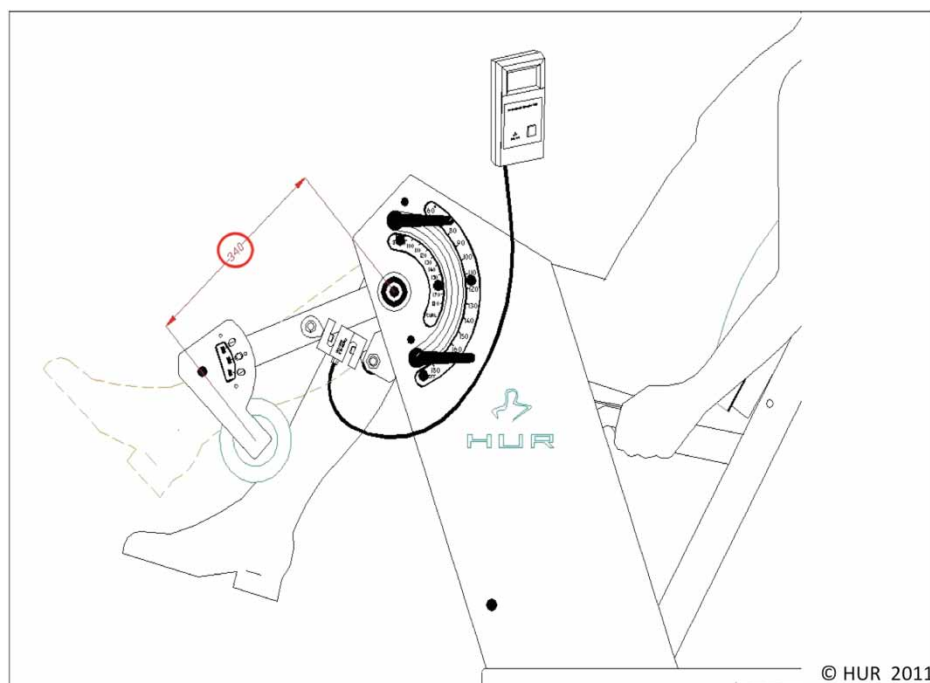


FIGURE 1 Diagram of the PR1 attachment to the HUR® 5530. The solid line indicates the position of the lower limb during knee extension and the dashed line indicates the position of the knee during knee flexion.

to a laptop computer, peak force, and force curves for each contraction can be displayed and analyzed. While the cost of the PR1 and associated software is about three times that of a HHD, it is still considerably less than a dynamometer such as the Biodex®. The PR1 unit could be a practical and affordable alternative for use in clinical rehabilitation practice and in a research setting as it may overcome some of the key limitations of MMT and HHD (i.e. tester experience and tester strength), and may be more feasible to purchase than a Biodex® dynamometer as it can be attached to the equipment that may already exist in the clinic or rehabilitation facility. However, the reliability and validity of this device compared with a gold-standard strength assessment tool has not been reported in the literature (Martin et al, 2006). Therefore, the purpose of this study was to examine the test-retest and inter-rater reliability of the PR1, as well as the validity compared with the gold-standard Biodex® dynamometer in measuring knee flexion and extension strength in healthy adults to determine its usefulness in a clinical or research setting.

METHODS

Participants

Participants were healthy, recreationally active individuals with no known current lower extremity injuries. Individuals were excluded if they reported any history of cardiovascular, neuromuscular, or musculoskeletal disorders that would prevent maximal effort during strength testing. This study was approved by the University of British Columbia research ethics board and informed consent was obtained from all participants. Participants were recruited among staff, faculty, and students at the University of British Columbia in September 2011. A sample size of $n = 10$ was needed to provide a power of 82% to determine an intra-class correlation coefficients (ICC) of 0.70 with two observations per subject (Walter, Eliasziw, and Donner, 1998).

Instrumentation

Isometric strength of the knee flexors and extensors was assessed using the HUR® 5530 leg extension/curl rehab machine, (HUR Limited, Kokkola, Finland), connected to the PR1 unit (HUR Limited, Kokkola, Finland), and the Biodex® System 4 Pro (Biodex Medical, Shirley, NY, USA). The PR1 consists of a hand-held display unit and a HMD1005B Tension and Compression Load Cell™

(HMD1005B; Yuyao Tongyong Meter Co., Ltd, China) and measures force production in kilograms (kg). The manufacturer of the HMD1005B reports a full-scale repeatability value of 0.02% for the load cell itself. The load cell was placed in series between fixed anchor points on the HUR® 5530 unit creating an isometric strength-testing unit with a fixed lever arm length (Figure 1). The Biodex® System 4 Pro is an isokinetic dynamometer allowing for testing of multiple joints in isokinetic, isometric, or isontonic modes. It is attached to a Windows-based PC running the Biodex Advantage Software for recording of peak and average torque in Newton meters (Nm) (Biodex Medical Systems, 2012).

Procedures

This study was a test-retest reliability and criterion-related validity investigation that took place over two separate days (Figure 2). Participants were asked to attend two testing sessions (Visit 1 and 2), scheduled one week apart. For those who were not able to attend both sessions, at the end of the first visit, alternative testing visits were arranged 2–14 days from testing day 1 based on equipment availability. Two independent testers completed all measures. This was a new piece of equipment, and testers familiarized themselves with the equipment, reviewed the manual and had practiced using the equipment over several days before inviting participants in for testing. Inter-rater reliability was determined by comparing values obtained using the PR1 by Testers 1 and 2 during the same visit (Visit 1). Test-retest reliability was determined by comparing values obtained using the PR1 by Tester 1 from two separate visits (Visit 1 and 2). Criterion-related validity was determined by comparing values obtained by using the PR1 (Tester 1) and Biodex® (Tester 2) on the same testing day. The order of knee flexion or extension was alternated for each participant, with even numbered participants starting with knee flexion and odd numbered participants with knee extension. All testing was completed on the participants' dominant leg (determined by asking participants to identify which leg they would kick a soccer ball with).

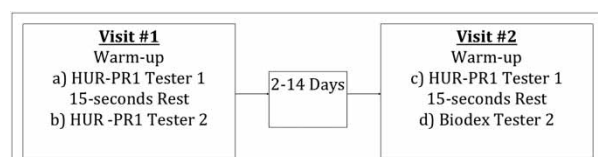


FIGURE 2 Order of testing.

The PR1 unit was calibrated at the start of each day of testing in accordance with the manufacturer specifications, using a 40 kg weight (HUR Labs, 2011). Participants performed a 5-min warm up on a cycle ergometer at a self-selected cadence and resistance followed by a 3-min rest period prior to undertaking PR1 testing. Following the initial explanation of study procedures, participants were positioned on the HUR® 5530. The axis of rotation of the swing arm was aligned with the lateral epicondyle of the femur and the lowest edge of the ankle pad was positioned 2 cm above the lateral malleolus. Stabilization straps were secured at the hip and thigh prior to testing trials (Figure 3). As only the back pad for the resistance training equipment could be adjusted, knee angle could not be set the same for each participant. For each participant, knee angle was measured by a goniometer for both knee flexion and knee extension trials, as knee angle differed from person to person and test (extension versus flexion), based on placing the ankle above (for knee flexion) or below (for knee extension) the ankle pad. Mean knee angle for knee flexion was 34.5° (range 26–43°) and mean knee angle was 56.9° for knee extension (range 45–65°). Finally, participants were instructed to use the support handles at the side of the machine. Prior to testing, participants performed 1–2 warm-up contractions (subjective 50% of anticipated maximum) for familiarization.



FIGURE 3 Photo of participant setup on the HUR machine.

The Biodex® was calibrated prior to each participant in accordance with the manufacturer specifications (Biodex Medical Systems, 2012). The lateral epicondyle of the knee was aligned with the center of the axis of rotation of the dynamometer and participants were stabilized with a waist strap, two crossed shoulder straps, and a strap over the thigh of the test leg. The lower leg attachment was adjusted to 2 cm above the malleoli and was comfortable but tight (Figure 4). For each person, the knee angle was preset to match the angle measured during the PR1 trial for both the flexion and the extension test on the Biodex®. Once setup for the movement (knee flexion or extension) was complete, each participant performed 1–2 subjective 50% maximum voluntary contractions for familiarization, and participants were instructed to use the support handles at the side of the machine.

For both the PR1 and Biodex®, participants then performed three maximal voluntary isometric contractions trials lasting 3 s each, with a 15-s rest break between contractions. As this was a healthy population we did not expect any problems with muscle recruitment and therefore 3 s was sufficient to achieve maximal contraction. Average peak time for extension was 2.30 s and for flexion was 1.99 s. Participants were instructed to exert maximal effort for the entire duration and were provided with standardized verbal



FIGURE 4 Photo of participant setup on the Biodex machine.

encouragement to “contract as hard and fast as possible” for each trial.

Muscular strength was quantified as the peak isometric torque production during the maximal voluntary contractions. For testing using the PR1, torque was calculated using the following equation, as per the manufacturer’s descriptions:

Actual torque [Nm] = measured force [kg] * sin 45 [°] * 0.16 [m] * 9.81 [m/s²], where sin 45 represents the angle between the load cell and the resistance machine and 0.16 m represents the distance between the axis of rotation and point of load cell attachment (HUR Labs, 2011).

Limb weight was not adjusted for during the knee flexion trials as the PR1 automatically subtracts the weight of the limb before measurement begins. For measures of knee extension strength using the PR1, peak torque was adjusted for limb weight by adding the weight of the limb as measured by the Biodex®, at the same angle for all participants. For trials using the Biodex®, peak torque for each contraction was recorded using Biodex® Advantage System 4 software (Biodex Medical, USA). For all trials, maximum peak torque was recorded as the highest torque achieved over the three trials.

Statistical methods

Statistical analysis was completed using SPSS Version 19 (IBM, Chicago, IL, USA). Descriptive data, including mean and standard deviations (SD), were used to summarize participants’ demographic characteristics as well as peak torque for flexion and extension as measured by each tester on each visit day. Test-retest and inter-rater reliability of peak torque measures for flexion and extension were assessed using ICC_{2,1} in order to determine not only the correlation between values but also the agreement (Shrout and Fleiss, 1979). The 95% confidence intervals were calculated using SPSS with the lower bound set at 0.0. ICC was determined to be good if 0.75, and excellent and appropriate for clinical use, if 0.90 (Portney and Watkins, 2009). Criterion-related validity for values obtained from the PR1 compared with values obtained from the Biodex® was determined using ICC_{2,1}. Bland–Altman plots were also constructed to visualize agreement between the two measurement tools (Bland and Altman, 1986). The difference in scores between the two tools for each participant was plotted against the mean peak torque scores for each participant using the PR1 and the Biodex®. The 95% limits of agreement (LOA) were

calculated as LOA = mean difference ± 2 SD of the difference.

RESULTS

Participant characteristics are presented in Table 1. Fifteen individuals agreed to participate in the study. Due to scheduling difficulties, one participant was only able to complete day one testing, and for this participant only inter-rater reliability was assessed. Three participants were only able to participate in day 2 of testing, therefore only criterion-related validity was assessed. This resulted in a sample size of $n = 11$ for test-retest reliability, $n = 12$ for inter-rater reliability, and $n = 14$ for criterion-related validity using the PR1 and the Biodex®.

Reliability

Test-retest reliability for peak knee flexion torque was excellent, ICC_{2,1} = 0.96 (95% CI: 0.85, 0.99), and test-retest reliability for peak knee extension torque was excellent ICC_{2,1} = 0.96 (95% CI: 0.87, 0.99) (Table 2). Inter-rater reliability for peak knee flexion torque was excellent, ICC_{2,1} = 0.95 (95% CI: 0.85, 0.99). Inter-rater reliability for peak knee extension torque was excellent ICC_{2,1} = 0.97 (95% CI: 0.91, 0.99) (Table 2).

Criterion-related validity

The PR1-Biodex® comparison for peak torque during knee flexion was good, ICC_{2,1} = 0.75 (95% CI: 0.38, 0.92) (Table 3). The PR1-Biodex® comparison for peak torque during knee extension was poor, ICC_{2,1} = 0.37 (95% CI: 0.0, 0.73). Data for knee extension using the PR1 were also examined adjusting for weight of the leg. This reduced the agreement even further. The PR1-Biodex® comparison for peak torque during knee extension with adjustment for weight of the leg was ICC_{2,1} = 0.28 (95% CI: 0.0,

TABLE 1 Participant characteristics ($n = 15$).

Participant characteristics	All participants mean (SD)
Age (years)	34.3 (10.3)
Height (m)	1.70 (0.08)
Weight (kg)	68.7 (18.5)
BMI (kg/m ²)	23.8 (3.7)
Gender n (%)	
Male	6 (40)
Female	9 (60)

TABLE 2 Torque (nM) and ICC associated with test-retest reliability measurements: (a) intra-rater $n = 11$ and (b) inter-rater $n = 12$.

	Mean (SD)	ICC (95% CI)
(a)		
<i>Flexion</i>		
Day 1	85.0 (32.1)	0.96 (0.85–0.99)
Day 2	80.9 (30.0)	
<i>Extension</i>		
Day 1	180.5 (56.1)	0.96 (0.87–0.99)
Day 2	175.0 (54.8)	
(b)		
<i>Flexion</i>		
Tester 1	91.7 (38.3)	0.95 (0.85–0.99)
Tester 2	88.3 (36.3)	
<i>Extension</i>		
Tester 1	194.3 (71.8)	0.97 (0.91–0.99)
Tester 2	188.5 (72.2)	

TABLE 3 Torque (nM) and ICC associated with criterion-related validity ($n = 14$).

	Mean (SD)	ICC (95% CI)
<i>Flexion</i>		
HUR PR-1	81.8 (27.6)	0.75 (0.38–0.92)
Biodex	85.3 (20.7)	
<i>Extension</i>		
HUR PR-1	173.0 (50.7)	0.37 (0.00–0.73)
Biodex	144.7 (36.5)	
<i>Extension (adjusted)</i>		
HUR PR-1	191.5 (54.1)	0.28 (0.00–0.66)
Biodex	144.7 (36.5)	

0.66). In addition, Bland–Altman plots were constructed to assess the agreement of the two measures of muscular strength (PR1 and Biodex®) using the error score (Figures 5(a)–(c)). The majority of points fall within the LOA (± 2 SD) and no pattern of over- or under-estimation was noted for knee flexion, however the PR1 may over-estimate values for peak torque during knee extension when compared with the Biodex®.

DISCUSSION

The PR1 is purported by the manufacturer as a general-purpose portable strength-measuring device that is easy to use and interpret, and is more affordable than similar available tools for measuring isometric strength in fitness or rehabilitation settings. The PR1 can be used in conjunction with resistance training equipment by HUR® or other manufacturers of

resistance training equipment (HUR Labs, 2011). To our knowledge, this is the first study that has evaluated the reliability of the PR1 as it would be used in a clinical rehabilitation setting to monitor changes in muscular strength with a muscle performance program or to monitor recovery from an injury.

Our results demonstrated that the PR1 provides a reliable assessment of knee flexion and extension between different testers on the same day (inter-rater) and within the same tester over multiple days (test-retest). The ICCs for both values obtained from the peak value of three trials were greater than 0.90, indicating excellent reliability, and appropriate for clinical use (Portney and Watkins, 2009). Recent investigations of lower limb isometric muscle strength assessment using HHD demonstrated a good level of reliability for knee flexors and extensors, but this is not consistent across studies with reliability coefficients ranging from 0.49 to 0.99, with the use of stabilization straps typically increasing the reliability (Bohannon et al, 2011; Kolber and Cleland, 2005; Toonstra and Mattacola, 2012). Compared with this literature, we report reliability at the high end of reported ranges for isometric strength assessment for both knee flexion and knee extension using the PR1. The high reliability reported in our study may be due to eliminating the issues of assessor strength and body positioning that are important measurement issues with HHD, especially when assessing knee extensor strength.

Criterion-related validity of the PR1 compared with the Biodex® was on the border of good for knee flexion (ICC = 0.75, where ICC 0.75 is good) and poor for knee extension (Portney and Watkins, 2009). Bland–Altman plots were included to assess agreement between scores, because scores can be highly correlated but have poor agreement (Atkinson and Nevill, 1998). While the majority of points did fall within the LOA, these limits were quite wide and suggested that the differences in values obtained from the two measuring tools may be important clinically (Bland and Altman, 1986). Recent research has demonstrated that values of knee extensor strength measured using HHD with stabilization strap are highly correlated to values obtained using the Biodex® ($r = 0.86–0.88$); however, absolute HHD scores were 33.7–35.6 nM lower than scores from the Biodex® (Bohannon et al, 2011). This suggests that strength values obtained by HHD should not be used interchangeably with values of muscular strength obtained by a dynamometer, such as the Biodex®. This is consistent with our findings, namely that values of muscular strength obtained using the PR1 should not be used interchangeably with values of muscular strength obtained by a dynamometer such

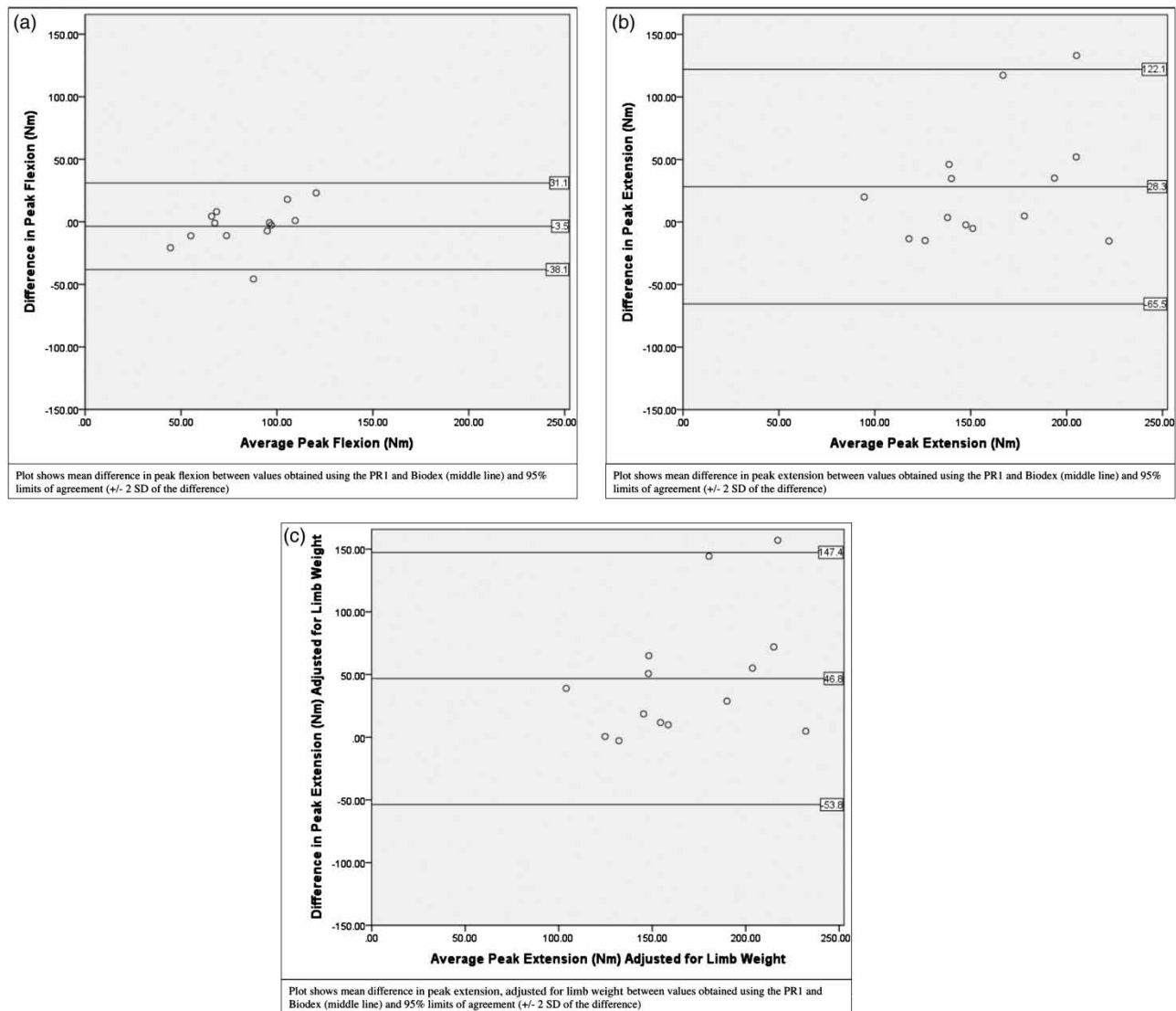


FIGURE 5 (a) Bland–Altman plot for peak knee flexion, (b) Bland–Altman plot for peak knee extension and (c) Bland–Altman plot for peak knee extension, adjusted for limb weight.

as the Biodex®, due to the demonstrated poor agreement between the two. Although efforts were made to standardized participant positioning between the PR1-HUR® 5530 setup and Biodex® setup, exact replication of the testing position in all cases was difficult. When the PR1 is attached to the HUR® 5530 it creates a fixed angle that may provide more or less mechanical efficiency, depending on an individual’s body size. Only the seat depth of the HUR® 5530 can be adjusted, whereas the seat angle and depth can be adjusted on the Biodex®, which may have resulted in different hip joint angles between the PR1-HUR® 5530 unit and the Biodex®. This likely contributed to some of the differences in values obtained because the muscle length for two-joint knee flexors and extensors would have been altered by the

positioning, resulting in a change in force that can be generated.

The Biodex® automatically calculates the weight of the limb and accounts for the effect of gravity when reporting torque values in both flexion and extension. The PR1 takes weight of the limb into account when testing knee flexion. The weight of the limb is registered when the leg is in place prior to the movement but the recorder is zeroed before the muscular strength measure is recorded. With clinical use of the PR1, it is unlikely that weight of the limb would be included in measures of knee extension (which requires work against gravity). Adjusting for weight of the leg in examining criterion-related validity reduced the PR1–Biodex® agreement. This may be due to the fact that limb weight on the Biodex® was

measured at a fixed angle across all participants, which may have been different than each individual's knee angle when seated on the HUR 5530 during knee extension measurement. Therefore, in clinical practice, no adjustment for weight of the limb is required when using the PR1 recorder where reliability within or between different clinicians performing the strength testing is the primary concern.

Limitations

Limitations of this study include the inability to exactly replicate hip joint angles between the PR1-HUR® 5530 unit and Biodex®, which may have contributed to the difference in values obtained using the two measurement tools. We did not control for participant's dietary intake, hydration level, sleep, or activity levels on the day of or prior to testing and the time of day that testing occurred was not consistent for all participant. However, there is also limited ability to control these factors in clinical practice and a useful tool should display good reliability and validity without controlling for these. As well, while our power calculation reveals we do have adequate power to detect an ICC of 0.70, the sample size is small which is reflected in the large confidence intervals seen. The small sample size also resulted in lower variability in the absolute strength scores across participants, which is also a limitation and may limit generalizability from this study sample of healthy adults to patient populations or elite athletes. Overall, despite these limitations, excellent test-retest and inter-rater reliability were found for knee flexion and extension, and good criterion validity was still obtained for knee flexion.

CONCLUSION

In summary, the PR1 is a reliable tool that can be used in conjunction with a leg flexion/extension resistance machine to assess isometric strength of the knee flexor and extensor muscles in healthy adults. However, absolute values may not be comparable to other objective strength assessment tools in a clinical setting. Therefore, the PR1 could be a valuable outcome tool for monitoring change in knee flexion and extension muscular strength in a clinical rehabilitation setting, including with assessment by two different therapists, but values obtained using the PR1 cannot be reported interchangeably with values recorded using other strength assessment tools.

Acknowledgments

The manufacturers of the equipment did not fund this study.

Declaration of interest: The authors report no conflicts of interest.

REFERENCES

- Atkinson G, Nevill AM 1998 Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine* 26: 217–238
- Biodex Medical Systems 2012 Biodex System 4 Pro 2012 <http://www.biodex.com/physical-medicine/products/dynamometers/system-4-pro-0>
- Bland JM, Altman DG 1986 Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1: 307–310
- Bohannon RW, Bubela DJ, Wang YC, Magasi SR, Gershon RC 2011 Adequacy of belt-stabilized testing of knee extension strength. *Journal of Strength and Conditioning Research* 25: 1963–1967
- Brill PA, Macera CA, Davis DR, Blair SN, Gordon N 2000 Muscular strength and physical function. *Medicine and Science in Sport and Exercise* 32: 412–416
- Cuthbert SC, Goodheart GJ, Jr 2007 On the reliability and validity of manual muscle testing: A literature review. *Chiropractic and Osteopathy* 15: 4
- Drouin JM, Valovich-mcLeod TC, Shultz SJ, Gansneder BM, Perrin DH 2004 Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European Journal of Applied Physiology* 91: 22–29
- Durfee WK, Iazzo PK 2006 *Encyclopedia of Medical Devices and Instrumentation*, 2nd edn. Volume 6, pp 62–71. Hoboken, NJ, John Wiley & Sons
- Ericsson YB, Roos EM, Dahlberg L 2006 Muscle strength, functional performance, and self-reported outcomes four years after arthroscopic partial meniscectomy in middle-aged patients. *Arthritis and Rheumatism* 55: 946–952
- Hasegawa R, Islam MM, Lee SC, Koizumi D, Rogers ME, Takeshima N 2008 Threshold of lower body muscular strength necessary to perform ADL independently in community-dwelling older adults. *Clinical Rehabilitation* 22: 902–910
- HUR Labs 2011 Performance Recorder PR1 Manual 2011 <http://www.hurlabs.com/index.php?id=143>
- Keating JL, Matyas TA 1996 The influence of subject and test design on dynamometric measurements of extremity muscles. *Physical Therapy* 76: 866–889
- Kolber MJ, Cleland JA 2005 Strength testing using hand-held dynamometry. *Physical Therapy Reviews* 10: 99–112
- Martin HJ, Yule V, Syddall HE, Dennison EM, Cooper C, Aihie Sayer A 2006 Is hand-held dynamometry useful for the measurement of quadriceps strength in older people? A comparison with the gold standard Biodex dynamometry. *Gerontology* 52: 154–159
- Portney L, Watkins MP 2009 *Foundations of Clinical Research: Applications to Practice*, 3rd edn. Upper Saddle River, NJ, Prentice Hall
- Salem GJ, Wang MY, Young JT, Marion M, Greendale GA 2000 Knee strength and lower- and higher-intensity functional performance in older adults. *Medicine and Science in Sports and Exercise* 32: 1679–1684

Shrout PE, Fleiss JL 1979 Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin* 86: 420–428

Toonstra J, Mattacola CG 2012 Test-retest reliability and validity of isometric knee flexion and extension measurement using three methods of assessing muscle strength. *Journal of Sport Rehabilitation* (Epub ahead of print)

Walter SD, Eliasziw M, Donner A 1998 Sample size and optimal designs for reliability studies. *Statistics in Medicine* 17: 101–110

White LJ, McCoy SC, Castellano V, Gutierrez G, Stevens JE, Walter GA, Vandenborne K 2004 Resistance training improves strength and functional capacity in persons with multiple sclerosis. *Multiple Sclerosis* 10: 668–674