






Please cite the Published Version

McNabb, Katherine , Sanchez, Maria B , Selfe, James , Reeves, Neil D  and Callaghan, Michael  (2024) Handheld dynamometry: validity and reliability of measuring hip joint rate of torque development and peak torque. PLoS One, 19 (8). e0308956 ISSN 1932-6203

DOI: <https://doi.org/10.1371/journal.pone.0308956>

Publisher: Public Library of Science

Version: Published Version

Downloaded from: <https://e-space.mmu.ac.uk/635396/>

Usage rights:  [Creative Commons: Attribution 4.0](https://creativecommons.org/licenses/by/4.0/)

Additional Information: This is an open access article which first appeared in PLoS ONE

Data Access Statement: All primary data files are available from the <https://e-space.mmu.ac.uk/> database (<https://doi.org/10.23634/MMU.00634821>).

Enquiries:

If you have questions about this document, contact openresearch@mmu.ac.uk. Please include the URL of the record in e-space. If you believe that your, or a third party's rights have been compromised through this document please see our Take Down policy (available from <https://www.mmu.ac.uk/library/using-the-library/policies-and-guidelines>)

RESEARCH ARTICLE

Handheld dynamometry: Validity and reliability of measuring hip joint rate of torque development and peak torque

Katherine McNabb¹*, María B. Sánchez¹, James Selfe¹, Neil D. Reeves^{2,3}, Michael Callaghan^{1,4,5}

1 Department of Health Professions, Faculty of Health and Education, Manchester Metropolitan University, Manchester, United Kingdom, **2** Department of Life Sciences, Faculty of Science and Engineering, Manchester Metropolitan University, Manchester, United Kingdom, **3** Lancaster Medical School, Faculty of Health and Medicine, Lancaster University, Lancaster, United Kingdom, **4** Centre for Musculoskeletal Research, Manchester Academic Health Sciences Centre, University of Manchester, Manchester, United Kingdom, **5** Department of Physiotherapy, Manchester University Hospitals NHS Foundation Trust, Manchester, United Kingdom

* These authors contributed equally to this work.

* katherine.mcnabb@stu.mmu.ac.uk



OPEN ACCESS

Citation: McNabb K, Sánchez MB, Selfe J, Reeves ND, Callaghan M (2024) Handheld dynamometry: Validity and reliability of measuring hip joint rate of torque development and peak torque. PLoS ONE 19(8): e0308956. <https://doi.org/10.1371/journal.pone.0308956>

Editor: Benjamin F. Mentiplay, La Trobe University, AUSTRALIA

Received: January 16, 2024

Accepted: August 1, 2024

Published: August 16, 2024

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: <https://doi.org/10.1371/journal.pone.0308956>

Copyright: © 2024 McNabb et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data Availability Statement: All primary data files are available from the <https://e-space.mmu.ac.uk/database> (<https://doi.org/10.23634/MMU.00634821>).

Abstract

Introduction

Measuring rate of torque development (RTD) and peak torque (PT) for hip muscle performance presents challenges in clinical practice. This study investigated the construct validity of a handheld dynamometer (HHD) versus an isokinetic dynamometer (IKD), and intra-rater repeated reliability for RTD and PT and their relationship in hip joint movements.

Methods

Thirty healthy individuals (mean age = 30 ± 8 years, 13 males) underwent two test sessions in a single day. RTD (0–50, 0–100, 0–150, 0–200ms) and PT normalised to body mass in maximal voluntary isometric contractions were measured using a HHD and an IKD in hip flexion, extension, abduction, adduction, internal and external rotation.

Results

For validity between the devices, RTD₀₋₅₀ exhibited the largest significant systematic bias in all hip movements (3.41–11.99 Nm·s⁻¹ kg⁻¹) and widest limits-of-agreement, while RTD₀₋₂₀₀ had the lowest bias (-1.33–3.99 Nm·s⁻¹ kg⁻¹) and narrowest limits-of-agreement. For PT, agreement between dynamometers was observed for hip flexion (0.08 Nm·kg⁻¹), abduction (-0.09 Nm·kg⁻¹), internal (-0.01 Nm·kg⁻¹), and external rotation (0.05 Nm·kg⁻¹). For reliability, intra-rater intraclass correlation coefficient (ICC_{2,1}) ranged from moderate to good in RTD₀₋₅₀ and RTD₀₋₁₀₀ (0.5–0.88), and good to excellent in RTD₀₋₁₅₀ and RTD₀₋₂₀₀ (0.87–0.95) in all movements. The HHD displayed excellent intra-rater, relative reliability values (ICC_{2,1}) in all movements (0.85–0.95). Pearson's correlation revealed good linear correlation between PT and RTD₀₋₁₅₀ and RTD₀₋₂₀₀ in all movements ($r = .7$ to $.87$, $p < .001$).

Funding: The author(s) received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Conclusion

Validity analysis demonstrated significant systematic bias and lack of agreement in RTD measures between the HHD and IKD. However, the HHD displays excellent to moderate intra-rater, relative reliability for RTD and PT measures in hip movements. Clinicians may use the HHD for hip muscle PT assessment but note, late phase RTD measures are more reliable, valid, and relate to PT than early phase RTD. Additionally, the correlation between RTD and PT at various time epochs was examined to better understand the relationship between these measures.

Introduction

In individuals with hip-related pain, clinicians commonly use peak torque (PT) parameters to assess the maximum force production of a group of muscles, as previous research has observed a reduction in PT measures in several hip muscles during a maximal voluntary isometric contraction (MVIC) in these individuals [1, 2]. Consequently, PT serves as a widely utilized strength metric for clinicians seeking to quantitatively define function and performance, and the effects rehabilitation has in individuals with hip-related pain [3]. However, given that many activities related to sport and daily living do not always demand maximum torque, other research suggests that rate of torque development (RTD) could offer insights into muscle performance prior to reaching PT [4].

RTD is a strength parameter of interest to clinicians and researchers as it provides valuable insights into the neuromuscular characteristics and functional capabilities of individuals. RTD measures how quickly an individual or group of muscles can generate torque during the early phase of contraction [5, 6]. It reflects the performance of fast movements in sporting tasks such as sprinting, jumping, or kicking, as well as in daily functional movements such as correcting balance and changing direction [7].

While these two muscle strength parameters, RTD and PT, offer assessments of distinct aspects of muscle function, PT is known to have a role in determining RTD [6] and therefore establishing their correlation in hip muscle performance is crucial for understanding the interplay between maximum strength and speed of torque generation. Using incremental time epochs to measure RTD allows analysis of various stages in the contraction which are considered to have differing factors influencing the RTD and therefore provide information that could help design targeted rehabilitation to address individual impairments [8, 9].

A laboratory-based isokinetic dynamometer (IKD) is commonly used to measure RTD, but a handheld dynamometer (HHD) can be employed more conveniently in a clinical setting using an isometric contraction. Establishing concurrent validity between the two devices for RTD measurements in hip movements is necessary to give confidence in knowing how accurately the HHD measures the same construct as the IKD. Mentiplay et al. [10] revealed strong concurrent validity for hip flexion, extension, abduction, and adduction with the IKD (RTD ICC ≥ 0.75) however further research is needed to identify potential systematic bias between these two instruments when measuring RTD in hip movements.

Furthermore, previous research has demonstrated the HHD exhibits strong intra-rater repeated reliability for assessing RTD during hip movements flexion, extension, abduction, and adduction [10–12]. Further investigation is still needed to determine its accuracy in capturing RTD across different time epochs, as reliability varies across epochs ranging from 0–50ms to 0–300ms in these movements.

The reliability and validity of using the HHD to measure peak force in some hip movements has been confirmed in other studies [10, 13–15]. However, as far as the authors are aware, no study has yet investigated the agreement between the HHD with the IKD, and the intra-rater repeated reliability when measuring RTD across six hip movements in three cardinal planes.

The primary objective of this study was to establish the concurrent validity of the HHD against the IKD, and the intra-rater repeated reliability of the HHD when measuring RTD in the time epochs 0–50, 0–100, 0–150 and 0–200ms, and PT, during hip flexion, extension, abduction, adduction, internal and external rotation movements in healthy adults.

Materials and methods

Study design

This was an observational study using a test-retest design with two identical test sessions. It was conducted in a movement laboratory at Manchester Metropolitan University, England. All tests were conducted by a single physiotherapist with 25 years clinical experience (first author).

Recommendations from the Guidelines for Reporting Reliability and Agreement Studies [16] were used, and outcome measures recorded were RTD_{50} , RTD_{100} , RTD_{150} , RTD_{200} ($Nm \cdot s^{-1}$) and PT (Nm) for hip flexion, extension, abduction, adduction, internal and external rotation, using an IKD and a HHD.

Participants

A sample of 30 healthy adults were recruited from university staff, students, friends, and family between 25/9/2020 and the 18/12/2020. Individuals between 18–50 years were eligible for the study with participants comparable in age with individuals experiencing hip-related pain [17]. Exclusion criteria included any self-reported history of hip, groin, lumbar, or lower limb pain or injury that had interfered with function, walking or caused the individual to seek treatment in the preceding 12 months; previous or current significant hip pathology; systemic disease affecting the muscular or nervous systems.

All procedures were approved by the Faculty of Health and Education, ethics committee Manchester Metropolitan University (EthOS ID 11792) and conducted in accordance with the 2013 Helsinki declaration. Informed written consent was obtained from all participants prior to entering the study.

Instrumentation

A fixed laboratory based IKD (Humac Norm (Cybex), Computer Sports Medicine Inc., Stoughton, MA, USA) and a HHD (Model 01165, Lafayette Instrumentation) were used to record measurements in each test session (Fig 1).

Isometric torque data from the IKD, sampled at 100Hz, was exported to a data acquisition system (Labchart 8, AD Instruments), where the sampling rate was maintained at 100Hz. Additionally, a zero-phase shift low-pass filter with a cut-off frequency of 50 Hz was applied [18]. The HHD data, sampled at 40Hz, was exported to an Excel spreadsheet (Microsoft Excel, USA). Subsequently, numerical data from both devices was manually extracted for analysis. Prior to testing each participant, both dynamometers were calibrated as per manufacturers' instructions.

Experimental procedure and design

All participants underwent two test sessions, separated by a minimum of 30-minutes. During the first session they were tested first using the IKD, and second with the HHD, to measure



Fig 1. Isokinetic dynamometer (left) and Lafayette handheld dynamometer (right). Photos used with permission from copyright owner.

<https://doi.org/10.1371/journal.pone.0308956.g001>

both RTD and PT in the six hip movements. In the second session the measurements were repeated using only the HHD. The order of test positions (Fig 2) was consistent and arranged to prevent individual muscles being tested succinctly with differing hip movements, minimise position changes, and reduce time burden to the participant. Immediately prior to the first test

	Hip movement position for isokinetic dynamometer and handheld dynamometer testing.					
	Flexion	Extension	Abduction	Adduction	Internal Rotation	External Rotation
Position using IKD						
Position using HHD						
Point of HHD application. (Measured to the inferior edge of transducer pad.)	Anterior thigh, 5cm above the superior pole of the patella.	Posterior tibia, in line with 5cm above superior tip of lateral malleolus.	Lateral lower leg, in line with 5cm above superior tip of lateral malleolus.	Medial tibia, in line with 5cm above superior tip of lateral malleolus.	Lateral lower leg, in line with 5cm above superior tip of lateral malleolus.	Medial tibia, in line with 5cm above superior tip of lateral malleolus.
Moment arm for HHD	Superior tip of the greater trochanter to 5cm above the superior pole of the patella.	Superior tip of the greater trochanter to 5cm above superior tip of lateral malleolus.	Superior tip of the greater trochanter to 5cm above superior tip of lateral malleolus.	Superior tip of the greater trochanter to 5cm above superior tip of lateral malleolus.	Superior tip of the greater trochanter to lateral knee joint line.	Superior tip of the greater trochanter to lateral knee joint line.

Fig 2. Participant’s positions used for testing for the isokinetic dynamometer (IKD) and the handheld dynamometer (HHD); point of application and moment arm definition for the HHD.

<https://doi.org/10.1371/journal.pone.0308956.g002>

session anthropometric measurements were taken and the International Physical Activity Questionnaire (IPAQ), short form was completed to establish participants' physical activity levels. To enable comparison of torque measurements between the IKD and the HHD, the external moment arms around the hip joint were measured in meters (m), using a tape measure (Fig 2) at the start of test session 1. Participants undertook a 5-minute submaximal warm-up on a static exercise bike. Prior to executing the MVIC for testing, participants performed familiarization trials consisting of two submaximal isometric contractions for each hip movement, on both devices [19].

Clinical feasibility of the HHD was a priority and therefore HHD testing positions were selected first and determined based on good reliability results from previous studies (ICC 0.7–0.98) [11, 15, 20, 21]. We aimed to replicate the IKD positions with those of the HHD, but the pre-programmed IKD configuration limited exact replication.

With both dynamometers, four trials of MVIC were performed, with 30 second rest between each trial, and instruction to push as 'hard' as possible for three seconds to record PT. This was followed by a further four trials of MVIC, to measure RTD, with 30 seconds rest between each trial, but with the alternative instruction to push as 'fast and hard' as possible for ~ 1 second to encourage rapid muscle contraction [19, 22]. Countermovement, seen as a movement of the limb in the opposite direction prior to rapid contraction, should be avoided [19] and trials were repeated if this was observed. Participants rested whilst set up was adjusted for the next hip movement. Uniform instruction and standardised verbal encouragement were given throughout [23]. The right limb was tested for all participants.

Participants' measurements with the IKD adhered to the manufacturer's instructions for each hip movement. The IKD rotational axis was visually aligned with the greater trochanter for hip flexion, extension, abduction, and adduction, while alignment for internal and external rotation followed the line of the femur through the anterior knee joint. The transducer pad was securely strapped to the limb.

Following this, participants transitioned to a physiotherapy plinth, where measurements were taken using the HHD using the same contraction protocol as the IKD. Participants optimized stabilization by holding the plinth where required.

Data extraction

The numerical raw torque data (in Nm) for the IKD was extracted from the Labchart trace. For the HHD, numerical raw force data (in N) was extracted and converted to torque (Nm) with multiplication by the external moment arm length in meters (m).

RTD was calculated as the slope of the torque-time curve (Δ torque / Δ time) [19] and measured as Newton-meters per second ($\text{Nm}\cdot\text{s}^{-1}$). Each MVIC trial generated four distinct time epochs each starting from the onset of torque production: 0–50, 0–100, 0–150, and 0–200ms [8].

The onset of torque production was determined manually by adding two Newton-meters to the baseline, which was calculated as the mean of three values from the visual flat line over a 500ms period before the observed change in data values [4]. The consistent method of calculation for the onset of torque production was applied for both the HHD and IKD. Numerical torque values were then extracted from the torque trace for the IKD and the Excel spreadsheet for the HHD at 50, 100, 150 and 200ms after torque onset. RTD was calculated for each time epoch. The highest RTD value among the four trials, for each time epoch, was retained for statistical analysis.

For the IKD, PT for each MVIC trial was identified as the highest value observed on visual inspection of the torque trace. For the HHD, PT for each MVIC trial was automatically

generated and displayed as a numerical value in the Excel spreadsheet. The highest PT value among the four MVIC trials was retained for statistical analysis [5]. Results were then normalised to body mass. The outcome variables were, normalised RTD 0–50, 0–100, 0–150, 0–200ms ($\text{Nm}\cdot\text{s}^{-1}\text{kg}^{-1}$) and normalised PT ($\text{Nm}\cdot\text{kg}^{-1}$).

Statistical analysis

All statistical analyses were performed in IBM SPSS version 27.0 (IBM Corp. in Armonk, NY). Normality of the data was determined using the Shapiro-Wilk test with the data conforming to normal distribution. Descriptive statistics (means \pm standard deviations (SD)) were calculated for all RTD and PT measures for each test session. The mean difference between test sessions 1 and 2 are presented for RTD and PT measurements to allow assessment of systematic bias between sessions.

Bland-Altman analyses with 95% limits of agreement (LOA) were calculated for all measures to examine the systematic difference between the HHD and the IKD. These analyses provide a visualisation of the bias between the measurement methods for each hip movement [24] and determine the agreement between the HHD and IKD systems.

The mean difference (bias) was analysed using a one sample t-test and considered significant if the 95% confidence intervals (95%CI) of the mean difference did not include the line of equality (bias) = 0 [25]. The LOA were calculated using the equation: $\text{MD} \pm 1.96 \cdot \text{SD}$, where MD is the mean difference between measurement methods and SD the corresponding standard deviation [26].

Intra-rater, test-retest reliability of using the HHD to measure RTD and PT were assessed using the two-way random effects intraclass correlation coefficient ($\text{ICC}_{2,1}$), with 95% CI [27]. ICC values were considered excellent (≥ 0.90), good (0.89–0.75), moderate (0.74–0.5), or poor (< 0.05) [28].

The absolute reliability of the HHD RTD and PT was assessed by calculating the standard error of measurement (SEM) using the square root of the mean squared error obtained from a two-way ANOVA. The minimal detectable change (MDC) was calculated using the formula $\text{MDC} = \text{SEM} \times 1.96 \times \sqrt{2}$ [27]. Both SEM and MDC were converted to percentages of the mean results.

Pearson correlation was used to assess the correlation between RTD_{0-50} , RTD_{0-100} , RTD_{0-150} , RTD_{0-200} and PT when measured with the IKD.

Results

All 30 participants data were used in the statistical analysis (mean age = 30 ± 8 years; height = $1.70 \pm 0.08\text{m}$; mass = $70.55 \pm 11.76\text{kg}$), with 13 males included in the study. IPAQ results classified individuals as participating in low [6], moderate [11] and high [13] activity levels.

Concurrent validity of HHD versus IKD with RTD measures

Bland-Altman analysis showed a significant systematic bias between the HHD and the IKD, when measuring RTD in all six movements, and in all time epochs (RTD_{0-50} , RTD_{0-100} , RTD_{0-150} , RTD_{0-200}). The bias and the LOA for RTD are presented in numerical style in Tables 1–4. The mean difference was biased positively indicating measurements from the HHD yielded lower measures than the IKD in all time epochs, and in all hip movements, with one exception of hip extension RTD_{0-150} ($-1.33\text{Nm}\cdot\text{s}^{-1}\text{kg}^{-1}$).

A noticeable trend was evident in all hip movements, where the late phase time epochs (RTD_{0-150} , RTD_{0-200}) exhibit better agreement with lower bias and narrower LOA compared to the early phase time epochs (RTD_{0-50} , RTD_{0-100}).

Table 1. Intersession reliability of RTD 0-50ms measurements in hip movements using a handheld dynamometer, and agreement analysis with an isokinetic dynamometer.

	Intersession reliability								Agreement analysis		
	Test mean(SD) session 1 (Nm·s ⁻¹ kg ⁻¹)	Test mean(SD) session 2 (Nm·s ⁻¹ kg ⁻¹)	Difference(SD) session 1–2 (Nm·s ⁻¹ kg ⁻¹)	ICC _{2,1}	SEM (Nm·s ⁻¹ kg ⁻¹)	SEM %	MDC (Nm·s ⁻¹ kg ⁻¹)	MDC %	Bias (Nm·s ⁻¹ kg ⁻¹)	95% LOA (Nm·s ⁻¹ kg ⁻¹)	
										Lower	Upper
Hip Flexion	2.64 (1.21)	2.48 (1.89)	0.16 (1.23)	0.72	0.80	31	1.78	70	11.99	-10.0	35.0
Hip Extension	3.54 (1.21)	3.09 (0.95)	0.45 (1.25)	0.50	0.88	27	1.97	60	4.66	-5.9	15.2
Hip Abduction	3.30 (2.06)	3.00 (1.19)	0.34 (1.57)	0.72	1.11	36	2.49	80	4.67	-4.9	14.2
Hip Adduction	2.89 (1.10)	3.03 (1.20)	-0.13 (0.96)	0.79	0.68	23	1.52	51	3.41	-2.9	9.60
Hip Internal rotation	1.48 (0.76)	1.42 (0.63)	0.06 (0.60)	0.79	0.42	29	0.93	64	3.67	-0.9	8.27
Hip External rotation	1.40 (0.62)	1.51 (0.60)	-0.11 (0.47)	0.82	0.33	23	0.74	51	6.60	0.14	13.0

SD: Standard deviation, ICC: Intraclass correlation coefficient ICC_{2,1} SEM: Standard error of measurement, MDC: Minimal detectable change, Bias: mean of differences between measurement methods, 95% LOA: 95% Limits of agreement

<https://doi.org/10.1371/journal.pone.0308956.t001>

Bland-Altman plots examining agreement between the HHD and the IKD when measuring hip flexion RTD for each time epoch are shown in Fig 3. As an example of interpretation, the LOA between the HHD and the IKD for measuring RTD 0-50ms in hip flexion had a range of -10.0 Nm·s⁻¹ kg⁻¹ to 35.0 Nm·s⁻¹ kg⁻¹ with a statistically significant bias of 11.99 Nm·s⁻¹ kg⁻¹ (95% CI 0.004 to 0.156, p< 0.05). Bland-Altman plots for all other hip movements are in the S1 File.

Concurrent validity of HHD versus IKD with PT measures

Bland-Altman analysis showed no significant systematic bias between measurement methods when measuring PT for hip flexion (0.08, 95%CI 0.0–0.16, p = 0.05), abduction (-0.09, 95%CI

Table 2. Intersession reliability of RTD 0-100ms measurements in hip movements using a handheld dynamometer, and agreement analysis with an isokinetic dynamometer.

	Intersession reliability								Agreement analysis		
	Test mean(SD) session 1 (Nm·s ⁻¹ kg ⁻¹)	Test mean(SD) session 2 (Nm·s ⁻¹ kg ⁻¹)	Difference(SD) session 1–2 (Nm·s ⁻¹ kg ⁻¹)	ICC _{2,1}	SEM (Nm·s ⁻¹ kg ⁻¹)	SEM %	MDC (Nm·s ⁻¹ kg ⁻¹)	MDC %	Bias (Nm·s ⁻¹ kg ⁻¹)	95% LOA (Nm·s ⁻¹ kg ⁻¹)	
										Lower	Upper
Hip Flexion	3.90 (1.53)	3.76 (1.53)	0.13 (1.01)	0.85	0.98	19	2.18	42	8.69	0.0	17.4
Hip Extension	4.71 (1.87)	4.24 (1.47)	0.46 (1.41)	0.77	0.10	22	2.24	50	0.73	-7.0	8.40
Hip Abduction	4.06 (3.13)	3.93 (1.56)	0.13 (1.38)	0.85	0.98	24	1.11	55	5.79	-1.1	12.7
Hip Adduction	3.66 (1.41)	3.99 (1.68)	-0.33 (1.16)	0.84	0.82	21	1.83	48	1.98	-1.8	5.08
Hip Internal rotation	1.80 (0.96)	1.92 (0.80)	-0.06 (0.56)	0.88	0.41	22	0.92	49	2.06	-0.8	4.90
Hip External rotation	1.38 (0.62)	1.51 (0.59)	-0.11 (0.47)	0.87	0.36	19	0.81	44	3.90	-0.7	8.50

SD: Standard deviation, ICC: Intraclass correlation coefficient ICC_{2,1} SEM: Standard error of measurement, MDC: Minimal detectable change, Bias: mean of differences between measurement methods, 95% LOA: 95% Limits of agreement

<https://doi.org/10.1371/journal.pone.0308956.t002>

Table 3. Intersession reliability of RTD 0-150ms measurements in hip movements using a handheld dynamometer, and agreement analysis with an isokinetic dynamometer.

	Intersession reliability								Agreement analysis		
	Test mean(SD) session 1 (Nm·s ⁻¹ ·kg ⁻¹)	Test mean(SD) session 2 (Nm·s ⁻¹ ·kg ⁻¹)	Difference(SD) session 1-2 (Nm·s ⁻¹ ·kg ⁻¹)	ICC _{2,1}	SEM (Nm·s ⁻¹ ·kg ⁻¹)	SEM %	MDC (Nm·s ⁻¹ ·kg ⁻¹)	MDC %	Bias (Nm·s ⁻¹ ·kg ⁻¹)	95% LOA (Nm·s ⁻¹ ·kg ⁻¹)	
									Lower	Upper	
Hip Flexion	4.61 (1.51)	4.55 (1.53)	0.07 (0.92)	0.91	0.78	14	1.63	32	2.37	-1.9	6.6
Hip Extension	5.32 (2.02)	4.89 (1.74)	0.43 (1.24)	0.87	0.88	17	1.96	38	-1.33	-7.4	4.7
Hip Abduction	4.22 (1.87)	4.25 (1.69)	-0.30 (1.03)	0.91	0.73	17	1.63	39	3.99	-0.5	12.7
Hip Adduction	3.75 (1.44)	3.88 (1.60)	-0.13 (0.67)	0.95	0.47	12	1.05	28	1.12	-2.4	4.6
Hip Internal rotation	2.00 (0.89)	2.11 (0.88)	-0.11 (0.53)	0.90	0.38	18	0.84	41	1.07	-1.3	3.4
Hip External rotation	1.92 (0.87)	2.18 (0.87)	-0.25 (0.50)	0.89	0.36	17	0.80	39	1.72	-0.9	4.3

SD: Standard deviation, ICC: Intraclass correlation coefficient ICC_{2,1} SEM: Standard error of measurement, MDC: Minimal detectable change, Bias: mean of differences between measurement methods, 95% LOA: 95% Limits of agreement

<https://doi.org/10.1371/journal.pone.0308956.t003>

-0.23–0.05, $p = 0.2$), internal (-0.01, 95%CI -0.13–0.1, $p = 0.79$), and external rotation (-0.05, 95%CI -0.02–0.12, $p = 0.15$) and therefore the two devices showed agreement. However, a significant systematic bias between measurement methods was observed when measuring PT in hip adduction (-0.22, 95%CI -0.32- -0.11, $p = 0.001$) and extension (-0.95, 95%CI -1.2- -0.7, $p < 0.001$). The limits of agreement were lowest with hip external rotation (-0.32 to 0.42 Nm·kg⁻¹) and highest with hip extension (-2.27–0.37 Nm·kg⁻¹).

A Bland-Altman plot examining agreement between the IKD and the HHD when measuring hip flexion PT is shown in Fig 4 as an example. Bland-Altman plots for all other hip movements are in the S2 File. The bias and the LOA for PT are presented in Table 5.

Table 4. Intersession reliability of RTD 0-200ms measurements in hip movements using a handheld dynamometer, and agreement analysis with an isokinetic dynamometer.

	Intersession reliability								Agreement analysis		
	Test mean(SD) session 1 (Nm·s ⁻¹ ·kg ⁻¹)	Test mean(SD) session 2 (Nm·s ⁻¹ ·kg ⁻¹)	Difference(SD) session 1-2 (Nm·s ⁻¹ ·kg ⁻¹)	ICC _{2,1}	SEM (Nm·s ⁻¹ ·kg ⁻¹)	SEM %	MDC (Nm·s ⁻¹ ·kg ⁻¹)	MDC %	Bias (Nm·s ⁻¹ ·kg ⁻¹)	95% LOA (Nm·s ⁻¹ ·kg ⁻¹)	
									Lower	Upper	
Hip Flexion	4.49 (1.72)	4.40 (1.71)	0.08 (0.90)	0.93	0.55	14	1.22	32	0.73	4.1	-2.6
Hip Extension	5.33 (2.04)	4.90 (1.66)	0.42 (1.14)	0.89	0.81	16	1.81	35	0.73	-1.8	5.3
Hip Abduction	3.93 (1.57)	3.95 (1.49)	-0.02 (0.77)	0.93	0.55	14	1.22	31	1.75	-1.8	5.3
Hip Adduction	3.35 (1.18)	3.40 (1.39)	0.06 (0.64)	0.94	0.45	13	1.02	30	0.56	-1.9	2.9
Hip Internal rotation	1.95 (0.80)	2.08 (0.85)	-0.13 (0.54)	0.88	0.38	19	0.85	42	0.67	-1.1	2.5
Hip External rotation	1.86 (0.82)	2.08 (0.83)	-0.23 (0.43)	0.91	0.30	15	0.67	34	0.98	-1.0	3.0

SD: Standard deviation, ICC: Intraclass correlation coefficient ICC_{2,1} SEM: Standard error of measurement, MDC: Minimal detectable change, Bias: mean of differences between measurement methods, 95% LOA: 95% Limits of agreement

<https://doi.org/10.1371/journal.pone.0308956.t004>

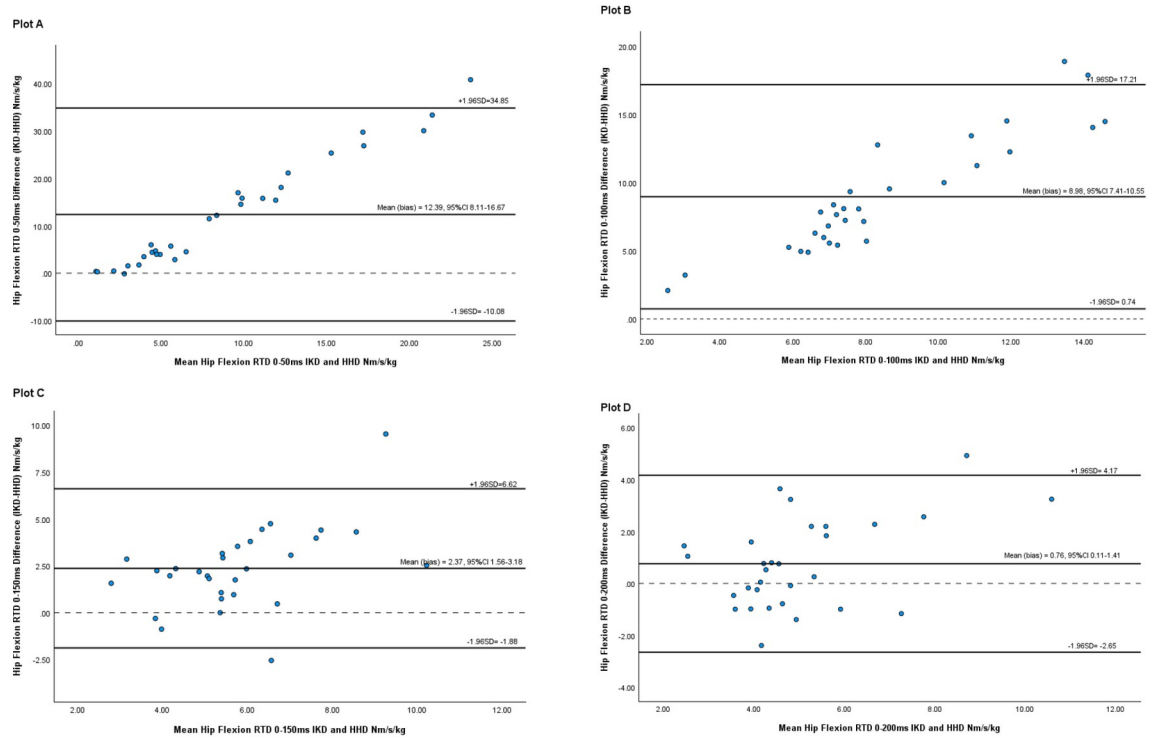


Fig 3. Plots A-D: Bland-Altman plots to show agreement between HHD and IKD when measuring RTD in hip flexion for group results.

<https://doi.org/10.1371/journal.pone.0308956.g003>

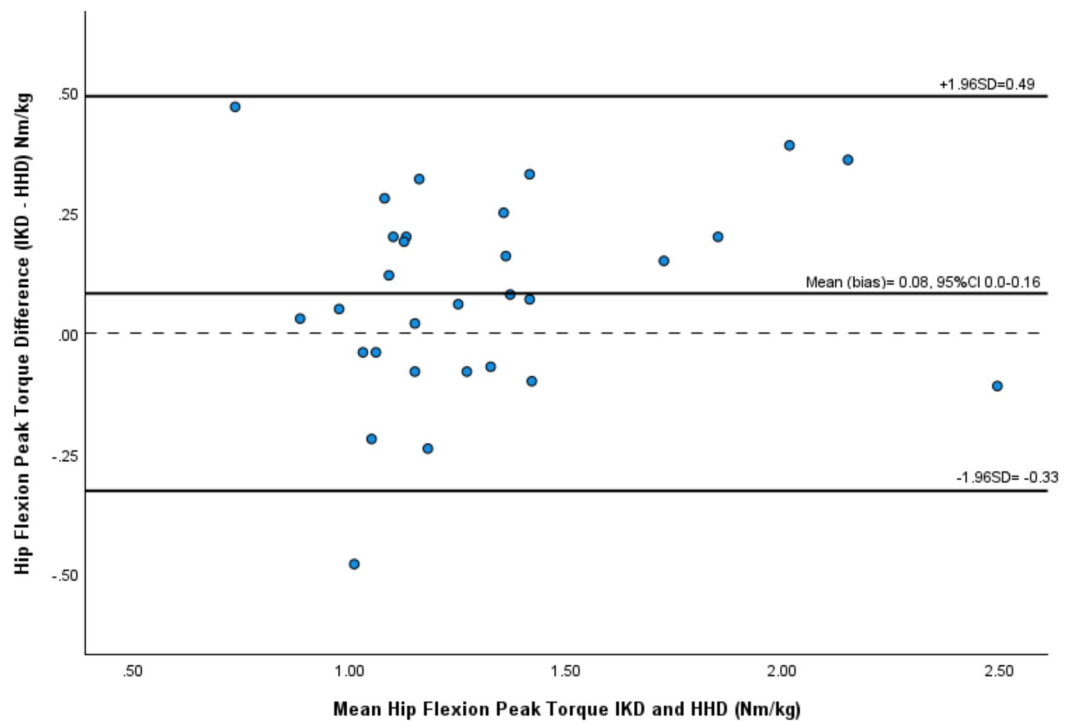


Fig 4. Bland-Altman plot to show agreement between IKD and HHD measuring hip flexion peak torque for group results.

<https://doi.org/10.1371/journal.pone.0308956.g004>

Reliability of RTD measures with HHD

Intra-rater, relative reliability results, between two test sessions, using the HHD to measure RTD in the hip movements are presented in Tables 1–4. In the six hip movements and four time epochs per movement, the relative reliability of using the HHD to measure the RTD, showed excellent or good reliability ($ICC_{2,1}$ 0.77–0.95) except in RTD₀₋₅₀ flexion ($ICC_{2,1}$ 0.72), extension ($ICC_{2,1}$ 0.5) and abduction ($ICC_{2,1}$ 0.72) which showed moderate reliability. A trend was apparent in all six hip movements showing the absolute measurement variation (SEM %) was highest in the lowest RTD time epochs, ranging from 23–36% in RTD₀₋₅₀ and 19–24% in RTD₀₋₁₀₀, and absolute measurement variation was lower in the higher time epochs, 12–18% in RTD₀₋₁₅₀, and 13–19% in RTD₀₋₂₀₀. The MDC% was also highest in RTD₀₋₅₀ (51–80%) and lowest in the higher time epochs RTD₀₋₁₅₀ (28–41%), RTD₀₋₂₀₀ (30–42%).

Reliability of PT measures with HHD

The relative reliability of using the HHD to measure PT was excellent or good for all six hip movements ($ICC_{2,1}$ 0.85–0.95). Absolute measurement variation (SEM) ranged between 0.08 and 0.2 $Nm \cdot kg^{-1}$ and as a percentage, 10–15%. MDC was lowest in hip abduction (22%) and highest in hip internal rotation (35%) (Table 5).

Correlation of RTD with PT

A Pearson's product moment correlation revealed time epochs of RTD₁₅₀ and RTD₂₀₀ (r range = .62 to .87 $p < 0.001$) correlated more strongly with PT measurements than the lowest time epoch RTD₅₀ (r range = .23 to .76). A complete list of correlations is presented in Table 6.

Discussion

This study demonstrates that the HHD can be used reliably to measure rate of torque development (RTD) in hip movements using a clinically feasible method. However, assessment of the concurrent validity through agreement parameters demonstrated that HHD measurements of late phase RTD₀₋₁₅₀ and RTD₀₋₂₀₀ have better agreement with the IKD than early phase RTD₀₋₅₀ and RTD₀₋₁₀₀. The presence of a significant systematic bias across all RTD time epochs

Table 5. Intersession reliability of peak torque measurements in hip movements using a handheld dynamometer, and agreement analysis with an isokinetic dynamometer.

	Intersession reliability								Agreement analysis		
	Test mean(SD) session 1 ($Nm \cdot kg^{-1}$)	Test mean(SD) session 2 ($Nm \cdot kg^{-1}$)	Difference(SD) session 1–2 ($Nm \cdot kg^{-1}$)	$ICC_{2,1}$	SEM ($Nm \cdot kg^{-1}$)	SEM %	MDC ($Nm \cdot kg^{-1}$)	MDC %	Bias ($Nm \cdot kg^{-1}$)	95% LOA ($Nm \cdot kg^{-1}$)	
										Lower	Upper
Hip Flexion	1.27 (0.38)	1.29 (0.37)	-0.02 (0.26)	0.91	0.18	14	0.40	32	0.08	-0.33	0.50
Hip Extension	1.80 (0.58)	1.72 (0.51)	0.08 (0.30)	0.95	0.20	12	0.45	26	-0.95	-2.27	0.37
Hip Abduction	1.29 (0.40)	1.28 (0.38)	0.15 (0.18)	0.95	0.13	10	0.28	22	-0.09	-0.83	0.65
Hip Adduction	1.08 (0.29)	1.14 (0.34)	-0.06 (0.23)	0.85	0.16	15	0.36	32	-0.26	-0.76	0.33
Hip Internal rotation	0.72 (0.25)	0.75 (0.27)	-0.03 (0.16)	0.92	0.11	15	0.24	35	-0.01	-0.60	0.59
Hip External rotation	0.66 (0.21)	0.63 (0.20)	0.04 (0.10)	0.94	0.08	12	0.17	26	0.05	-0.32	0.43

SD: Standard deviation, ICC: Intraclass correlation coefficient $ICC_{2,1}$ SEM: Standard error of measurement, MDC: Minimal detectable change, Bias: mean of differences between measurement methods, 95% LOA: 95% Limits of agreement

<https://doi.org/10.1371/journal.pone.0308956.t005>

Table 6. Pearson correlation between rate of torque development and peak torque in hip movements.

Hip Movement	Rate of torque development time epoch			
	0-50ms	0-100ms	0-150ms	0-200ms
Flexion	.76*	.83*	.62*	.81*
Extension	.63*	.78*	.87*	.79*
Abduction	.23	.52**	.86*	.79*
Adduction	.43**	.70*	.74*	.81*
Internal Rotation	.31	.54**	.75*	.75*
External Rotation	.68*	.78*	.81*	.78*

**Correlation is significant at 0.01 level (2-tailed)

* Correlation is significant at 0.05 level (2-tailed)

<https://doi.org/10.1371/journal.pone.0308956.t006>

indicated the HHD measurements yielded lower RTD values than the IKD and may not be considered an equivalent representation of measurements obtained with the IKD.

Peak torque (PT) measurements taken with the HHD exhibited good to excellent intra-rater, repeated reliability in hip movements and demonstrated close agreement with the IKD when measuring hip flexion, abduction, internal and external rotation.

Although the ICC had consistently high or very high values, indicating excellent reliability indices, these were accompanied by high values for SEM and MDC. This indicates that the HHD for most RTD and PT measurements have a measurement error greater than 10% and might not be able to detect clinically important changes in RTD or PT performance for hip movements.

Correlation analysis was also performed to inform clinicians that there was a high association between RTD in the later phases (RTD₁₅₀ and RTD₂₀₀) and PT.

Capturing torque measurements over extremely short time periods requires a tool sensitive enough to accurately detect subtle changes. Examining the validity of the HHD for measuring RTD in hip movements by comparing it to the IKD, and assessing their agreement, sheds light on the practical implications of this. The results from this present study suggest that the HHD RTD values in all hip movements become more consistent with those of the IKD as the contraction progresses, with late phase RTD (RTD₀₋₁₅₀ and RTD₀₋₂₀₀) demonstrating more accurate results. Whilst no other research has examined the validity across several time epochs in six hip movements, these findings are in agreement with Mentiplay et al. [10] who reported a moderate to good concurrent validity between the HHD and the IKD for RTD₀₋₂₀₀ in hip flexion, extension, abduction, and adduction ($r = .80-.92$) in healthy young adults.

The larger observed differences in early phase RTD measures between the two devices are likely influenced by the discrepancy in sampling frequency, with the IKD generating five sampling points compared to the HHD's two sampling points every 50ms. While the HHD has been utilized in prior research for measuring RTD (RTD₀₋₁₀₀ and RTD₀₋₂₀₀) in individuals with femoroacetabular impingement syndrome [29] and may suffice for clinical purposes, the IKD offers the potential for greater accuracy and better representation of RTD if necessary.

The agreement analysis further highlights a statistically significant systematic difference between the two devices across all hip movements, indicating the HHD consistently yielded lower RTD values compared to the IKD. Consequently, while the results from the two devices are not interchangeable, in clinical practice where only one device is employed for assessment, achieving agreement with another device may not be as crucial.

Due to the limited literature specifically examining RTD measurements between dynamometers, the clinical consequences of bias in a particular direction were not predefined.

Instead, trends in agreement were identified, noting that later-phase RTD measurements exhibited lower bias and narrower confidence intervals. While establishing clinically meaningful thresholds for bias is important, valuable insights into the agreement between measurements from HHDs and IKDs are still provided by the findings from this present study. Now that it is understood the HHD consistently measured lower than IKD, these findings can help inform clinical decision-making and guide future research on setting acceptable levels of bias. Further research is needed to help define acceptable limits of agreement in RTD measurements between dynamometers.

Examination of individual hip movements' agreement results at RTD_{0-150} and RTD_{0-200} reveal that hip abduction exhibited the most significant systematic bias between the dynamometers. This discrepancy is likely attributable to differences in participant positioning. The selected position aimed to enhance set up rigidity, crucial for RTD assessment, by optimizing participant stabilization and belt fixation to the physiotherapy plinth. Previous research demonstrated reduced error levels (SEM%) in the supine position (2.9%) compared to side lying (8.5%) when measuring PT [30]. While both Mentiplay et al. [10] and Ishoi et al. [11] also utilized the supine position in their RFD studies using the HHD, replicating this setup on the IKD in this current study was unfeasible due to its pre-programmed side lying configuration. Although the hip joint angle remains consistent with the two positions, further research has indicated that side lying tends to yield higher PT values than supine positioning [31, 32]. Consequently, this disparity likely contributed to the observed increase in systematic difference seen in the agreement results for hip abduction (bias RTD_{0-200} $1.75 \text{ Nm}\cdot\text{s}^{-1} \text{ kg}^{-1}$). However, repeated reliability measures for the supine position using the HHD are excellent (ICC 0.93) providing clinicians with confidence in this position for repeated measures whilst being mindful that it may produce lower absolute values than side lying.

Conversely for PT, there was close agreement between the two devices for hip flexion, abduction, internal and external rotation as the bias was low and 95% CIs included 0. As with RTD, dissimilar testing positions potentially attributed to significant systematic bias observed for hip extension and adduction with the HHD yielding higher PT measurements compared to the IKD. Despite other research exploring various positions when measuring PT with a HHD in hip movements, a universally agreed-upon best position remains lacking [33]. The position used for hip extension is variable in other studies. Bazett-Jones et al. [21] reported poor concurrent validity between the HHD and IKD ($r = 0.19$) for hip extension PT when the identical position was used for both methods, aligning with the supine position at a 0° hip joint angle used in this study for the IKD. In contrast, Mentiplay et al. [10] adopted the prone hip extension position matching the position used for the HHD in this study and observed strong concurrent validity between the two methods. Hence, it may be advisable for future studies to consider the prone hip extension position for improved validity.

Good to excellent intra-rater repeated reliability was demonstrated for RTD and PT with the HHD across all hip movements, consistent with findings from other studies [10, 11, 15]. More specifically, reliability levels of RTD improved with larger time epochs, exhibiting lower absolute measurement variation (SEM) thereby indicating that RTD_{0-150} and RTD_{0-200} are better suited for clinical measurement. These findings align with previous research involving healthy populations [10, 34].

Comparison of RTD and PT measurement variation using the HHD reveals that RTD measures exhibit greater variability than PT, consistent with previous research [10, 11]. Consequently, RTD measures are less precise, making it challenging to detect small but potentially clinically significant changes.

Variation in SEM levels may also be influenced by participant characteristics and differing populations. In this present study, SEM values for PT ranged from 10–15% which are similar

[15, 35] or higher than those reported in previous studies using the HHD [10, 11]. SEM levels RTD_{0-200} for hip flexion (14%), extension (16%), abduction (14%) and adduction (13%) are similar or slightly higher compared to those reported by Ishøi et al. [11], who found SEM levels for RTD_{0-200} in hip flexion (7.4%), extension (12.3%), abduction (13.8%) and adduction (14%) (age 25.4 ± 4.2 years). Similarly, Mentiplay et al. [10] using two assessors, reported lower SEM values for RTD_{0-200} , with hip flexion ranging from 9.65% to 11.68%, extension from 9.70% to 10.71%, abduction from 13.08% to 15.69% and adduction from 11.06–13.0% (age 22.87 ± 5.08 years). The higher variation in this study could be attributed to a broader age range and higher mean age (30 ± 8 years), along with greater heterogeneity in height and weight among subjects, resulting in increased variability.

These results suggest that the HHD may not reliably detect changes at the previously suggested 10% threshold considered clinically relevant for assessing muscle force improvements or deteriorations [36, 37]. However, in clinical populations such as individuals with hip osteoarthritis, the SEM for assessing peak force with the HHD was found to be lower (2.12–8.49%) [38] indicating the HHD may offer a more reliable assessment method in clinical populations, sensitive enough for detecting clinically significant changes.

Clinically useful MDC% values for PT measurements in hip flexion, extension, abduction, and adduction using the HHD in the current study (22–35%) are higher compared to those reported by Ishøi et al. [11] (MDC% 16–21%) and Mentiplay et al. [10] (MDC% 16–27%). However, individuals with hip pain can exhibit substantial deficits in peak force/torque ranging from 16–28% [17, 39–42] compared to healthy individuals, suggesting that peak force/torque changes in patients undergoing rehabilitation could potentially surpass these MDC values.

RTD MDC results are notably higher (RTD_{0-200} 30–35%) than PT values which has previously been observed 20–39% [11] and 27–43% [10]. Research is limited but significant RTD deficits have been observed within clinical populations with reduced RTD observed in hip abductors and extensors of females with patellofemoral pain (33–51%) [43] and 61–71% greater RTD in hip abduction and adduction in younger healthy women (age 21.8 ± 2.1 years) compared to older women fallers (> 60 years) [44].

This study revealed strong positive correlation between late phase RTD and PT in hip joint movements which has not previously been examined. Similarly late phase RTD correlated with PT in quadriceps and hamstring muscles [6]. In the context of rehabilitation, this correlation suggests that interventions aimed at increasing PT may concurrently improve late-phase RTD . Such insights are valuable for clinicians, as targeted rehabilitation commonly includes exercises to enhance PT and mitigate deficits.

Study limitations

The study had limitations, including the non-randomized order of hip movement testing to prevent individual muscles from being tested succinctly with differing hip movements. Additionally, conducting test sessions on the same day, rather than on different days as is typical in clinical settings, may have introduced fatigue potentially influencing the outcomes, and affecting the generalizability of the findings. However, the protocol was defined to reduce time demands on participants during the Covid-19 pandemic. While the consistent test order minimized variability between groups, we mitigated fatigue concerns by ensuring rest time between contractions and incorporating additional rest periods during transitions between different movements. Participant feedback and observations of fatigue levels guided the need for longer rest periods when warranted.

Another limitation was differing positions between the HHD and the IKD. While joint angles remained consistent for both dynamometers, the HHD participant positions were

chosen for clinical feasibility as opposed to the pre-programmed and standardized positions of the IKD, but this likely had a negative impact on the agreement results.

Lastly, the method chosen for calculating the onset of torque production for RTD aimed to achieve the highest possible precision [4]. However, this method is time-consuming and may not be practical in a clinical setting. To address this, an automatic force onset threshold can be set directly on the HHD, simplifying the process. Notably, the post-test calculations required to determine RTD values may present a barrier to RTD measurement in clinical practice. To address this, the development of accurate, automatic conversion within the HHD software is recommended. Alternatively, external software programmes can be used [10].

Conclusion

This study offers a comprehensive analysis in healthy subjects for RTD and PT using a HHD in hip movements and provides comparative analysis with measurements taken using an IKD. Results indicate that late phase RTD_{0-150} , and RTD_{0-200} , in all hip movements exhibit better reliability, lower SEM%, lower MDC%, and improved agreement with the IKD compared to early phase RTD_{0-50} . Therefore, these late phase measurements are recommended for use with the HHD.

RTD measurement with a belt stabilized HHD in hip movements (four trials of MVIC with the instruction to push as ‘fast and hard’ as possible to encourage rapid muscle contraction) is a novel approach, yet it offers a method that is accessible for clinical application. However, clinicians should be mindful of the differences in setup between the HHD and IKD, as these variations can impact validity and reliability.

Supporting information

S1 Checklist. Human participants research checklist.

(DOCX)

S1 File. S1 Appendix: Bland-Altman plots to show agreement of HHD with IKD measuring RTD in hip movements for group results.

(DOCX)

S2 File. S2 Appendix: Bland-Altman plots to show agreement of HHD with IKD measuring peak torque in hip movements for group results.

(DOCX)

Author Contributions

Conceptualization: Katherine McNabb, James Selfe, Neil D. Reeves, Michael Callaghan.

Data curation: Katherine McNabb.

Formal analysis: Katherine McNabb.

Investigation: Katherine McNabb.

Methodology: Katherine McNabb, Neil D. Reeves, Michael Callaghan.

Project administration: Katherine McNabb.

Resources: Katherine McNabb.

Software: Katherine McNabb.

Supervision: María B. Sánchez, James Selfe, Neil D. Reeves, Michael Callaghan.

Writing – original draft: Katherine McNabb, James Selfe, Neil D. Reeves, Michael Callaghan.

Writing – review & editing: Katherine McNabb, María B. Sánchez, Neil D. Reeves, Michael Callaghan.

References

1. Freke MD, Kemp J, Svege I, Risberg MA, Semciw A, Crossley KM. Physical impairments in symptomatic femoroacetabular impingement: a systematic review of the evidence. *British journal of sports medicine*. 2016; 50(19):1180–. <https://doi.org/10.1136/bjsports-2016-096152> PMID: 27301577
2. Maffiuletti NA, Bizzini M, Sutter R, Pfirrmann CW, Naal FD, Leunig M, et al. Hip muscle strength asymmetries and their associations with hip morphology and symptoms are sex-specific in patients with femoroacetabular impingement syndrome. *Physical Therapy in Sport*. 2020; 42:131–8. <https://doi.org/10.1016/j.ptsp.2020.01.010> PMID: 31995785
3. Mosler AB, Kemp J, King M, Lawrenson PR, Semciw A, Freke M, et al. Standardised measurement of physical capacity in young and middle-aged active adults with hip-related pain: recommendations from the first International Hip-related Pain Research Network (IHIPRN) meeting, Zurich, 2018. *British journal of sports medicine*. 2020; 54(12):702–10. <https://doi.org/10.1136/bjsports-2019-101457> PMID: 31857334
4. Buckthorpe M, Roi GS. The time has come to incorporate a greater focus on rate of force development training in the sports injury rehabilitation process. *Muscles, ligaments and tendons journal*. 2017; 7(3):435. <https://doi.org/10.1138/mltj/2017.7.3.435> PMID: 29387636
5. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology*. 2002; 93(4):1318–26. <https://doi.org/10.1152/jappphysiol.00283.2002> PMID: 12235031
6. Folland J, Buckthorpe M, Hannah R. Human capacity for explosive force production: neural and contractile determinants. *Scandinavian journal of medicine & science in sports*. 2014; 24(6):894–906. <https://doi.org/10.1111/sms.12131> PMID: 25754620
7. Rodríguez-Rosell D, Pareja-Blanco F, Aagaard P, González-Badillo JJ. Physiological and methodological aspects of rate of force development assessment in human skeletal muscle. *Clinical Physiology and Functional Imaging*. 2018; 38(5):743–62. <https://doi.org/10.1111/cpf.12495> PMID: 29266685
8. Andersen LL, Aagaard P. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European Journal of Applied Physiology*. 2006; 96(1):46–52. <https://doi.org/10.1007/s00421-005-0070-z> PMID: 16249918
9. Oliveira FBD, Oliveira ASC, Rizzato GF, Denadai BS. Resistance training for explosive and maximal strength: effects on early and late rate of force development. *Journal of sports science & medicine*. 2013; 12(3):402–8. PMID: 24149144
10. Mentiplay BF, Perraton LG, Bower KJ, Adair B, Pua YH, Williams GP, et al. Assessment of Lower Limb Muscle Strength and Power Using Hand-Held and Fixed Dynamometry: A Reliability and Validity Study. *PLoS One*. 2015; 10(10):e0140822. <https://doi.org/10.1371/journal.pone.0140822> PMID: 26509265
11. Ishøi L, Hölmich P, Thorborg K. Measures of hip muscle strength and rate of force development using a fixated handheld dynamometer: Intra-tester intra-day reliability of a clinical set-up. *International journal of sports physical therapy*. 2019; 14(5):715–23. PMID: 31598409
12. Takeda K, Tanabe S, Koyama S, Nagai T, Sakurai H, Kanada Y, et al. Intra- and inter-rater reliability of the rate of force development of hip abductor muscles measured by hand-held dynamometer. *Measurement in Physical Education and Exercise Science*. 2018; 22(1):19–24.
13. Fulcher ML, Hanna CM, Raina Elley C. Reliability of handheld dynamometry in assessment of hip strength in adult male football players. *Journal of Science and Medicine in Sport*. 2010; 13(1):80–4. <https://doi.org/10.1016/j.jsams.2008.11.007> PMID: 19376747
14. Thorborg K, Bandholm T, Hölmich P. Hip- and knee-strength assessments using a hand-held dynamometer with external belt-fixation are inter-tester reliable. *Knee Surgery, Sports Traumatology, Arthroscopy*. 2013; 21(3):550–5. <https://doi.org/10.1007/s00167-012-2115-2> PMID: 22773065
15. Martins J, da Silva JR, da Silva MRB, Bevilaqua-Grossi D. Reliability and Validity of the Belt-Stabilized Handheld Dynamometer in Hip- and Knee-Strength Tests. *Journal of athletic training*. 2017; 52(9):809–19. <https://doi.org/10.4085/1062-6050-52.6.04> PMID: 28787180
16. Kottner J, Gajewski BJ, Streiner DL. Guidelines for Reporting Reliability and Agreement Studies (GRRAS). *International Journal of Nursing Studies*. 2011; 48(6):659–60. <https://doi.org/10.1016/j.ijnurstu.2011.01.017> PMID: 21376316

17. Casartelli NC, Maffiuletti NA, Item-Glatthorn JF, Staehli S, Bizzini M, Impellizzeri FM, et al. Hip muscle weakness in patients with symptomatic femoroacetabular impingement. *Osteoarthritis and Cartilage*. 2011; 19(7):816–21. <https://doi.org/10.1016/j.joca.2011.04.001> PMID: 21515390
18. Cossich V, Maffiuletti NA. Early vs. late rate of torque development: Relation with maximal strength and influencing factors. *Journal of Electromyography and Kinesiology*. 2020; 55:102486. <https://doi.org/10.1016/j.jelekin.2020.102486> PMID: 33152680
19. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: physiological and methodological considerations. *European Journal of Applied Physiology*. 2016; 116(6):1091–116. <https://doi.org/10.1007/s00421-016-3346-6> PMID: 26941023
20. Thorborg K, Roos EM, Bartels EM, Petersen J, Hölmich P. Validity, reliability and responsiveness of patient-reported outcome questionnaires when assessing hip and groin disability: a systematic review. *British Journal of Sports Medicine [Internet]*. 2010; 44(16):[1 186 p.].
21. Bazett-Jones DM, Squier K. Measurement properties of hip strength measured by handheld dynamometry: reliability and validity across the range of motion. *Physical Therapy in Sport*. 2020; 42:100–6. <https://doi.org/10.1016/j.ptsp.2020.01.005> PMID: 31958744
22. Sahaly R, Vandewalle H, Driss T, Monod H. Maximal voluntary force and rate of force development in humans—importance of instruction. *European Journal of Applied Physiology*. 2001; 85(3):345–50. <https://doi.org/10.1007/s004210100451> PMID: 11560090
23. Sisto SA, Dyson-Hudson T. Dynamometry testing in spinal cord injury. *Journal of rehabilitation research and development*. 2007; 44(1):123. <https://doi.org/10.1682/jrrd.2005.11.0172> PMID: 17551866
24. Bland JM, Altman D. Statistical methods for assessing agreement between two methods of clinical measurement. *The lancet*. 1986; 327(8476):307–10. PMID: 2868172
25. Giavarina D. Understanding bland altman analysis. *Biochemia medica*. 2015; 25(2):141–51. <https://doi.org/10.11613/BM.2015.015> PMID: 26110027
26. Atkinson GD, Nevill AM. Statistical Methods For Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine. *Sports Medicine*. 1998; 26(4):217–38. <https://doi.org/10.2165/00007256-199826040-00002> PMID: 9820922
27. Weir JP. Quantifying test-retest reliability using the intraclass correlation coefficient and the sem. *Journal of Strength and Conditioning Research*. 2005; 19(1):231–40. <https://doi.org/10.1519/15184.1> PMID: 15705040
28. Portney LG, Watkins MP. *Foundations of clinical research: applications to practice*. 3rd ed. Upper Saddle River, N.J.: Pearson Education; 2009.
29. Ishøi L, Thorborg K, Kemp JL, Reiman MP, Hölmich P. Maximal hip muscle strength and rate of torque development 6–30months after hip arthroscopy for femoroacetabular impingement syndrome: A cross-sectional study. *Journal of science and medicine in sport*. 2021; 24(11):1110–5.
30. Thorborg K, Petersen J, Magnusson SP, Hölmich P. Clinical assessment of hip strength using a handheld dynamometer is reliable: Clinical assessment of hip strength. *Scandinavian Journal of Medicine & Science in Sports*. 2010; 20(3):493–501.
31. Widler KS, Glatthorn JF, Bizzini M, Impellizzeri FM, Munzinger U, Leunig M, et al. Assessment of hip abductor muscle strength. A validity and reliability study. *JBJS*. 2009; 91(11):2666–72. <https://doi.org/10.2106/JBJS.H.01119> PMID: 19884441
32. Waiteman MC, Garcia MC, Briani RV, Norte G, Glaviano NR, De Azevedo FM, et al. Can Clinicians Trust Objective Measures of Hip Muscle Strength From Portable Dynamometers? A Systematic Review With Meta-analysis and Evidence Gap Map of 107 Studies of Reliability and Criterion Validity Using the COSMIN Methodology. *Journal of orthopaedic & sports physical therapy*. 2023; 53(11):655–72. <https://doi.org/10.2519/jospt.2023.12045> PMID: 37787581
33. Stark T, Walker B, Phillips JK, Fejer R, Beck R. Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. *PM&R*. 2011; 3(5):472–9. <https://doi.org/10.1016/j.pmrj.2010.10.025> PMID: 21570036
34. Gonçalves BAM, Mesquita RNO, Tavares F, Brito J, Correia P, Santos P, et al. A new portable device to reliably measure maximal strength and rate of force development of hip adduction and abduction. *The Journal of Strength & Conditioning Research*. 2022. <https://doi.org/10.1519/JSC.0000000000003872> PMID: 35696597
35. Florencio LL, Martins J, da Silva MRB, da Silva JR, Bellizzi GL, Bevilacqua-Grossi D. Knee and hip strength measurements obtained by a hand-held dynamometer stabilized by a belt and an examiner demonstrate parallel reliability but not agreement. *Physical Therapy in Sport*. 2019; 38:115–22. <https://doi.org/10.1016/j.ptsp.2019.04.011> PMID: 31091492
36. Prentice WE, Kaminski TW, Scibek J. *Rehabilitation techniques for sports medicine and athletic training*. (No Title). 2004.

37. Chamorro C, Armijo-Olivo S, De la Fuente C, Fuentes J, Javier Chiroso L. Absolute reliability and concurrent validity of hand held dynamometry and isokinetic dynamometry in the hip, knee and ankle joint: systematic review and meta-analysis. *Open medicine*. 2017; 12(1):359–75. <https://doi.org/10.1515/med-2017-0052> PMID: 29071305
38. Vaz GF, Freire FF, Gonçalves HM, de Aviz MAB, Martins WR, Durigan JLQ. Intra-and inter-rater reliability, agreement, and minimal detectable change of the handheld dynamometer in individuals with symptomatic hip osteoarthritis. *Plos one*. 2023; 18(6):e0278086. <https://doi.org/10.1371/journal.pone.0278086> PMID: 37289803
39. Harris-Hayes M, Mueller MJ, Sahrmann SA, Bloom NJ, Steger-May K, Clohisy JC, et al. Persons with chronic hip joint pain exhibit reduced hip muscle strength. *The Journal of orthopaedic and sports physical therapy*. 2014; 44(11):890–8. <https://doi.org/10.2519/jospt.2014.5268> PMID: 25299750
40. Diamond LE, Wrigley TV, Hinman RS, Hodges PW, O'Donnell J, Takla A, et al. Isometric and isokinetic hip strength and agonist/antagonist ratios in symptomatic femoroacetabular impingement. *Journal of science and medicine in sport / Sports Medicine Australia*. 2016; 19(9):696–701. <https://doi.org/10.1016/j.jsams.2015.10.002> PMID: 26526760
41. Kierkegaard S, Mechlenburg I, Lund B, Soballe K, Dalgas U. Impaired hip muscle strength in patients with femoroacetabular impingement syndrome. *J Sci Med Sport*. 2017; 20(12):1062–7. <https://doi.org/10.1016/j.jsams.2017.05.008> PMID: 28595868
42. Bizzini M, Schaub G, Ferrari E, Monn S, Leunig M, Casartelli NC, et al. Hip muscle strength in male and female patients with femoroacetabular impingement syndrome: Comparison to healthy controls and athletes. *Physical Therapy in Sport*. 2023; 61:142–8. <https://doi.org/10.1016/j.ptsp.2023.03.010> PMID: 37054534
43. Nunes GS, Barton CJ, Serrão FV. Hip rate of force development and strength are impaired in females with patellofemoral pain without signs of altered gluteus medius and maximus morphology. *Journal of Science and Medicine in Sport*. 2018; 21(2):123. <https://doi.org/10.1016/j.jsams.2017.05.014> PMID: 28606466
44. Morcellii MH, Rossi DM, Karuka AH, Crozara LF, Hallal CZ, Marques NR, et al. Peak torque, reaction time, and rate of torque development of hip abductors and adductors of older women. *Physiotherapy theory and practice*. 2016; 32(1):45–52. <https://doi.org/10.3109/09593985.2015.1091870> PMID: 26756456