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A Ground-based Comparison of the Muscle Atrophy Research and Exercise System (MARES) and a Standard Isokinetic Dynamometer

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ABSTRACT

Introduction: International Space Station (ISS) crew members perform pre- and post-flight testing to assess changes in muscle strength associated with long-duration exposure to microgravity. Currently no reliable, standardized inflight strength data exist. An understanding of the timeline of strength changes during long-duration space flight will facilitate improved exercise prescription and enhance countermeasures evaluation. The aims of this investigation were to: 1) evaluate the test-retest reliability of a proprietary dynamometer, and 2) determine its agreement with a standard, commercially available isokinetic dynamometer used for pre- and post-flight medical assessment testing. *Methods:* Six males (179.5 ± 4.7 cm; 82.0 ± 8.7 kg; 31.3 ± 4.0 y) and 4 females (163.2 ± 7.3 cm; 63.2 ± 1.9 kg; 32.3 ± 6.8 y) completed 2 sessions on a standard, commercially available isokinetic dynamometer (NORM) and 2 sessions on the Muscle Atrophy Research and Exercise System (MARES) in a random, counterbalanced order. Peak torque values at 60° and $180° \cdot s^{-1}$ were obtained from 5 maximal repetitions of knee extension (KE) and knee flexion (KF). Total work at $180° \cdot s^{-1}$ was determined from the area under the torque versus displacement curve during 20 maximal repetitions of KE and KF. *Results:* Intraclass correlation coefficients were relatively high for both devices (0.90 to 0.99). However, ratios of the within-device standard deviation were 1.3 to 4.3 times higher on MARES. Only one dependent measure, KE peak torque at $60° \cdot s^{-1}$, exhibited good concordance between devices (rho = 0.91) and a small average difference (8.8 ± 16.7 Nm). *Conclusion:* MARES demonstrated acceptable test-retest reliability. However, due to poor agreement with NORM, it is not advisable to compare values obtained on these devices, e.g., to perform ground-based testing using NORM and inflight testing with MARES.

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 METHODS 2

2.1 Subjects 2

2.2 Equipment 3

2.3 Testing 3

2.4 Statistical Analyses 4

3.0 RESULTS 5

4.0 DISCUSSION 6

4.1 Acknowledgements 9

5.0 REFERENCES 10

TABLES & FIGURES

Table 1 Intraclass correlation coefficients (ICC) for HUMAC NORM and MARES 5

Table 2 Measures of reliability within devices and agreement between devices for HUMAC NORM and MARES 5

Figure 1-A Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for $\mathbf{KE_{PkT}60}$. 11

Figure 1-B Plot of NORM-MARES concordance with line of perfect concordance provided for reference. 11

Figure 2-A Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for $\mathbf{KF_{PkT}60}$. 12

Figure 2-B Plot of NORM-MARES concordance with line of perfect concordance provided for reference. 12

Figure 3-A Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for $\mathbf{KE_{PkT}180}$. 13

Figure 3-B Plot of NORM-MARES concordance with line of perfect concordance provided for reference. 13

Figure 4-A Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for $\mathbf{KF_{PkT}180}$. 14

Figure 4-B Plot of NORM-MARES concordance with line of perfect concordance provided for reference. 14

Figure 5-A Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for $\mathbf{KE_{TW}180}$. 15

Figure 5-B Plot of NORM-MARES concordance with line of perfect concordance provided for reference. 15

Figure 6-A Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for $\mathbf{KF_{TW}180}$. 16

Figure 6-B Plot of NORM-MARES concordance with line of perfect concordance provided for reference. 16

ACRONYMS

ESA	European Space Agency
ExPC	Exercise Physiology and Countermeasures Project
ISS	International Space Station
L-180	180 days before launch
L-60	60 days before launch
MARES	Muscle Atrophy Research and Exercise System
MEDB 5.3	Medical Volume B, requirement 5.3 (isokinetic testing)
NASA	National Aeronautics and Space Administration
Nm	Newton meter
R+5	5 days after return from flight (landing)
R+14	14 days after return from flight (landing)
R+30	30 days after return from flight (landing)
SD	Standard deviation
SOEP	Science and Operations Evaluation Plan

1.0 INTRODUCTION

Crew members of long-duration space expeditions complete standardized medical testing before and after space flight to evaluate changes in strength and endurance of major postural and locomotor muscle groups. Specifically, Medical Volume B, requirement 5.3 (MEDB) requires isokinetic testing of the extensor and flexor muscles of the knee, ankle, and trunk. Testing is conducted twice pre-flight (L-180 and L-60) and thrice post-flight (L+5, L+14, and L+30) using a standard, commercially available isokinetic dynamometer. Numerous studies have established both the validity[1] and the test-retest reliability of several commercially available isokinetic dynamometers (e.g., Biodex, Lido, and Cybex or HUMAC NORM).[1-13]

Currently, no standardized, reliable inflight strength data exist. In the absence of such data, there is very little understanding of the timeline of changes in muscle strength and endurance during space flight; such a timeline will enhance our understanding of the relative contributions of factors such as muscle atrophy and neuromuscular changes to muscle strength losses during space flight. For example, it is unknown whether strength losses occur in a linear fashion or whether they mirror those of aerobic capacity that occur mostly in the first few weeks of space flight.[14] In a 23-day unilateral limb suspension study, de Boer et al. reported a decrease in knee extensor torque of $1.06\% \cdot d^{-1}$ over the first 14 days and $0.68\% \cdot d^{-1}$ over the following 9 days.[15] A strength change timeline featuring greater losses during the first days of flight would likely have significant operational implications, as exercise countermeasures on the ISS currently are not scheduled during the first 7 days of flight and, anecdotally, may not begin until the third week of space flight. Additionally, inflight strength testing capabilities will enhance countermeasures evaluation and facilitate improved prescription of crew members' inflight exercise programs over the duration of their flight.

To address this gap in inflight strength testing capability, the European Space Agency (ESA) has developed the Muscle Atrophy Research and Exercise System (MARES). A MARES unit was delivered to the International Space Station (ISS) in early 2010 concurrently with the performance of this evaluation. MARES is capable of supporting a vast array of muscle tests during space flight. Operationally, the availability of MARES onboard the ISS will enable scientists to study strength changes during—not just following—space flight. However, before use as an inflight strength evaluation tool, it is essential to establish MARES's reliability and to determine how strength parameters obtained using MARES compare with those measured using a standard, ground-based dynamometer employed for standard medical tests.

Thus, the purpose of this investigation was two-fold: 1) to determine the test-retest reliability of isokinetic muscle strength and endurance measurements obtained using MARES, and 2) to quantify the agreement between muscle strength and endurance measurements obtained on a standard, commercially available isokinetic dynamometer and MARES.

2.0 METHODS

2.1 Subjects

Six males (179.5 ± 4.7 cm; 82.0 ± 8.7 kg; 31.3 ± 4.0 y) and 4 females (163.2 ± 7.3 cm; 63.2 ± 1.9 kg; 32.3 ± 6.8 y) volunteered to participate in this project. Subjects were required to be recreationally active and to pass a modified Air Force Class III physical examination. Subjects received written and verbal explanations of the testing protocols and provided written informed consent. The test protocols and procedures were reviewed and approved by the NASA Johnson Space Center's Committee for the Protection of Human Subjects.

2.2 Equipment

Testing sessions were conducted on 2 devices: 1) a standard, commercially available dynamometer (NORM; CSMI, Inc., Stoughton, MA), and 2) a proprietary dynamometer, MARES (NTE-SENER, Barcelona, Spain). Both dynamometers were calibrated before data collection per the manufacturer's recommendations.

2.3 Testing

Subjects performed 2 testing sessions each using NORM and MARES (4 total testing sessions) using a balanced, randomized, cross-over design. During each session, peak torque values were measured during 2 testing sets: 1) 5 maximal, discrete repetitions of isokinetic knee extension and knee flexion at $60° \cdot s^{-1}$ ($KE_{PkT}60$ and $KF_{PkT}60$), and 2) 21 maximal, continuous repetitions of knee extension and knee flexion at $180° \cdot s^{-1}$ ($KE_{PkT}180$ and $KF_{PkT}180$). The first repetition of the second testing set was discarded; repetitions 2 through 21 were analyzed. Total work was also determined for these 20 repetitions from the area under the torque versus displacement curve ($KE_{TW}180$ and $KF_{TW}180$). All testing was performed over a 75° range of motion (95° flexion to 20° extension) that was determined from a 90° anatomical reference measured by a goniometer. Warm up consisted of 4 submaximal repetitions and 2 maximal repetitions at the prescribed testing velocity before performance of that velocity-specific testing set; subjects rested 2 minutes between each warm up and test set.

All testing was conducted using the right leg with the exception of one subject who had a pre-existing right leg injury; for this subject, the left leg was used. Subjects were positioned uniformly on each device and the position settings recorded to enable a reproducible set up. Subjects completed both sessions within one device before proceeding to testing within the other.

Each testing session was separated by at least 2 days. Subjects refrained from any exercise in the 8 h before testing and from strenuous exercise 24 h prior to testing. NORM testing was conducted by two Exercise Physiology and Countermeasures Project (ExPC) personnel; MARES testing was similar but included the addition of a MARES engineer. MARES testing used the Science and Operations Evaluation Plan (SOEP) 7, Block 1 ($60° \cdot s^{-1}$) and Block 7 ($180° \cdot s^{-1}$). NORM data were obtained using the manufacturer-provided HUMAC software. MARES-generated .txt files were reduced using a MATLAB (MathWorks, Natick, MA) script written to extract or calculate the variables of interest. NORM data were gravity-corrected using a static limb weight obtained at 20° of knee extension. For MARES, subject torque, not shaft torque (both standard MARES outcome variables) was used for all data analysis.

2.4 Statistical Analyses

Reliability of dependent variables within devices was assessed by the intraclass correlation coefficient (ICC); between device reliability was determined using the ratio of the within-device standard deviations. Agreement between NORM and MARES was evaluated by: 1) average difference and 95% limits of agreement, 2) a calculation of concordance (rho), and 3) the correlation between the mean of measures versus the delta difference between measures (μ versus Δ). Mean of measures was calculated as the mean of all 4 testing sessions (2 using NORM, 2 using MARES). Delta difference was calculated as the difference between the mean of each subject's 2 NORM sessions and the 2 MARES sessions. Perfect concordance was defined as rho = 1.00. Increasing values of the correlation between the mean of measures versus the delta difference between measures (range = 0.00 to 1.00) was interpreted as an increase in bias. All data were analyzed using STATA (StataCorp LP, College Station, TX) and Excel 2007 (Microsoft Corp, Redmond, WA).

3.0 RESULTS

Intraclass correlation coefficients for NORM and MARES ranged from 0.90 to 0.99 (Table 1). Within-device standard deviations were 1.2 to 4.3 times larger for MARES than NORM (Table 2). Average differences between devices were high except for $KE_{PkT}60$ (8.8 Nm; 95% limits of agreement = -23.9 to 41.5 Nm) and $KE_{PkT}180$ (-3.3 Nm; 95% limits of agreement = -50.8 to 44.2 Nm) (Fig 1-6). Concordance (rho) was < 0.90 for all but one dependent measure ($KE_{PkT}60$: rho = 0.91; Table 2, Fig 1-6). Only $KE_{PkT}60$ exhibited a low correlation between the mean of measures versus the delta difference between measures (μ vs. Δ = -0.22; Table 2).

Table 1. Intraclass correlation coefficients (ICC) for HUMAC NORM and MARES.

	Intraclass correlation coefficients (ICC)	
	NORM	MARES
$KE_{PkT}60$	0.99	0.95
$KF_{PkT}60$	0.97	0.98
$KE_{PkT}180$	0.99	0.90
$KF_{PkT}180$	0.99	0.94
$KE_{TW}180$	0.99	0.99
$KF_{TW}180$	0.95	0.98

Table 2. Measures of reliability within devices and agreement between devices for HUMAC NORM and MARES.

	Ratio of within device SD[1]	Concordance rho[2]	Correlation of μ versus Δ[3]
$KE_{PkT}60$	1.92	0.91	-0.22
$KF_{PkT}60$	1.30	0.33	-0.47
$KE_{PkT}180$	3.85	0.87	-0.37
$KF_{PkT}180$	4.30	0.22	-0.80
$KE_{TW}180$	1.18	0.75	-0.67
$KF_{TW}180$	1.47	0.15	0.89

Notes: [1]Ratio > 1.0 indicates higher within-device SD for MARES; [2]rho value of 1.00 indicates perfect concordance; [3]correlation of 0.00 indicates no bias, i.e., consistent agreement between devices across the range of values.

4.0 DISCUSSION

This investigation sought both to determine the test-retest reliability of isokinetic muscle strength and endurance parameters obtained using MARES and to quantify the agreement between muscle strength and endurance measurements obtained on a standard, commercially available isokinetic dynamometer and those obtained using MARES. Although ICC's were moderate to high for all outcome variables on both devices signifying acceptable test-retest reliability, within-device standard deviations were 1.2 to 4.3 times larger for MARES than NORM indicating somewhat lower reliability for MARES. Overall, agreement between NORM and MARES was poor as evidenced by large average differences and 95% limits of agreement, low concordance rho values, and high correlations between the mean of measures versus the delta difference between measures.

The within-device reliability indices produced mixed results. On one hand, ICC values for MARES were moderate to high for all dependent measures, suggesting reproducibility from session 1 to 2. Conversely, ratios (MARES: NORM) of within-device standard deviations were greater than 1.0, corresponding to greater variability between sessions for MARES in comparison to NORM. Ultimately, given the ICC values for MARES, it appears reasonable to conclude that although MARES is more variable between sessions than NORM, MARES nonetheless provides acceptable test-retest reliability.

The three statistical measures employed to determine agreement between NORM and MARES yielded singular results: of the six dependent measures, only $KE_{PkT}60$ showed any promise as a parameter for which values obtained on one device might be used as a surrogate for the other. However, although the mean difference between devices for $KE_{PkT}60$ was small (8.8

Nm higher on NORM, or ~5% of the mean values for this study), the 95% limits of agreement were quite large, resulting in an unacceptable range of mean differences (-23.9 to 41.5 Nm).

Examination of the knee flexion data reveals differences between the two devices that are distinctively worse than those of the knee extension measures (Figures 2, 4, 6). This may be due to differences in the ergonomic setup between the two devices. Whereas NORM has a deep seat that provides support along the entire length of subjects' upper legs, the MARES seat is much more shallow and terminates around mid-femur leaving the distal portion of the upper leg unsupported. It is possible that this lack of support (and the resultant lack of restraint) allowed subjects to generate greater flexion torques on MARES by recruiting their hip extensors in addition to their knee flexors.

Although the results of this investigation are valuable, it is important that they are viewed with caution. Only ten subjects, representing a moderate range of physiologic strength, were tested. A comprehensive reliability study employing a much larger sample would be needed to more definitively establish MARES' reliability and validity. An investigation of this magnitude also would facilitate the development of regression equations that would allow us to compare values obtained on one device to those measured on the other.

In conclusion, the results of this single, relatively small-n investigation demonstrate that MARES is a reasonably reliable device that renders consistent measurements between two sessions. However, MARES does not produce values that are in consistent agreement with NORM. Thus, until further research suggests otherwise, it is not advisable to compare values obtained on one device to those obtained on the other. This is particularly relevant to future flight studies that will use MARES as an inflight testing device; to compare pre- and post-flight

strength measurements to those obtained inflight, pre- and post-flight strength testing should be conducted using MARES.

4.1 Acknowledgements

We would like to thank our subjects for their enthusiastic participation in this study. We are also grateful for the indispensable assistance of the MARES Engineering Team at Johnson Space Center: Neil Travis, Martin Bost, and Diane Byerly. Lastly, we thank Joaquim Castellsaguer, MARES Project Engineer, for his willingness to answer numerous questions regarding MARES design and operation.

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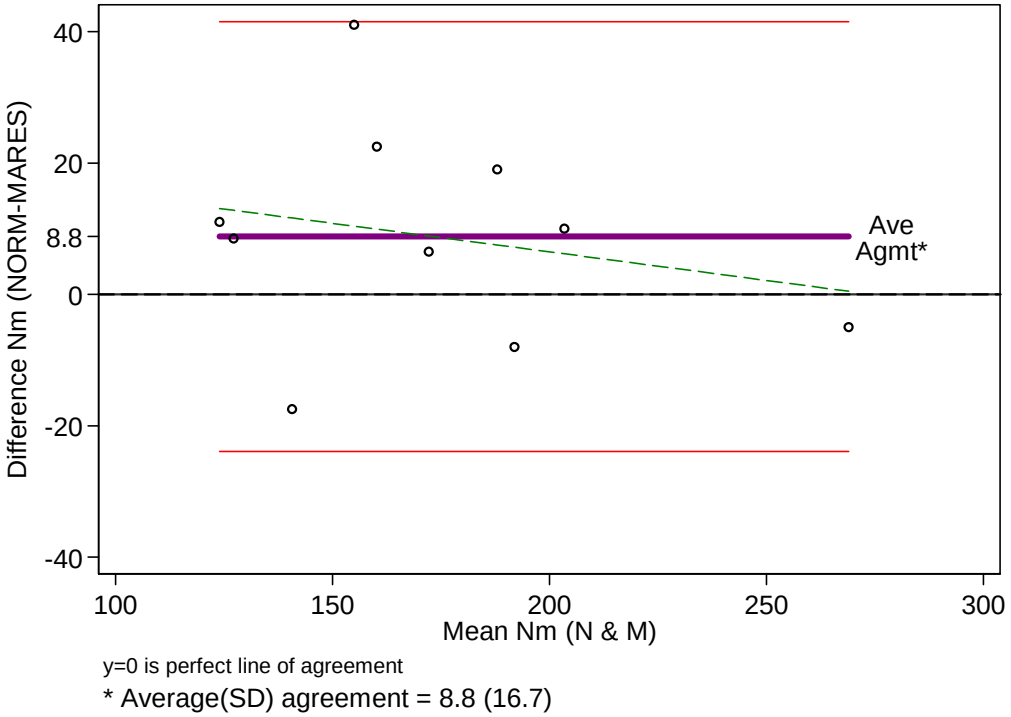

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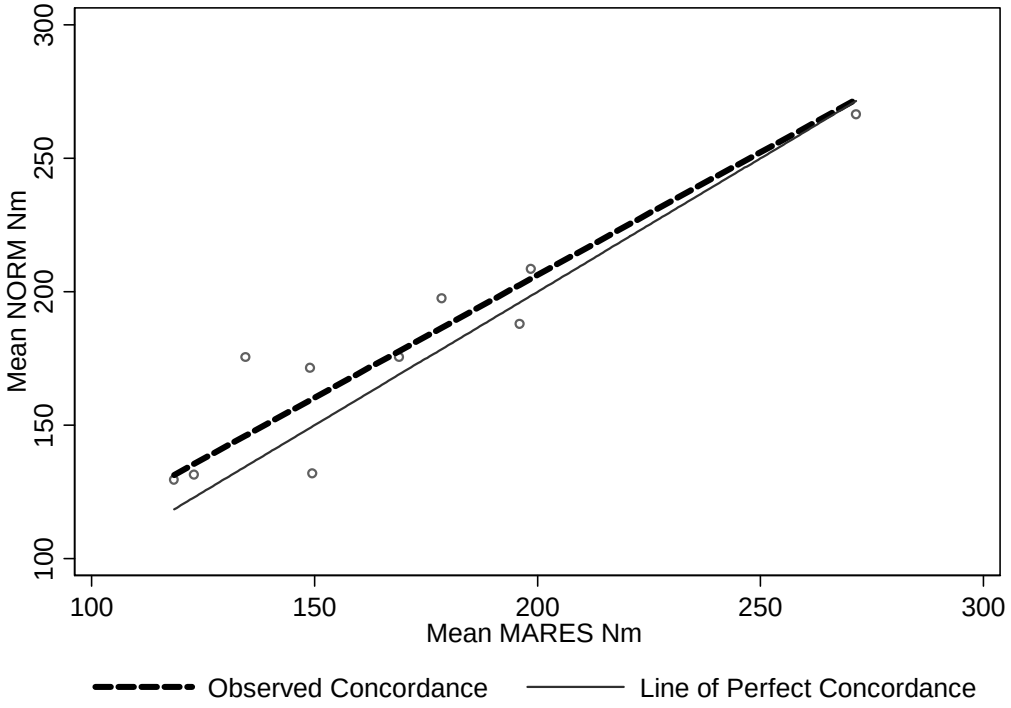
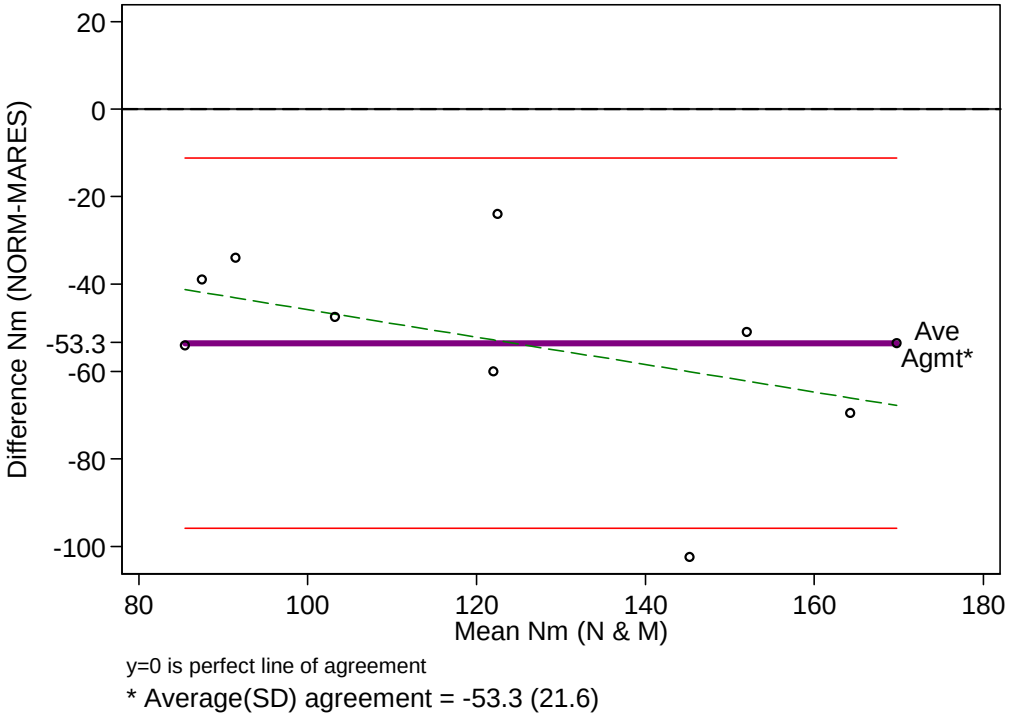


Figure 1. A: Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for $\mathbf{KE_{PkT}60}$. The thin dashed line represents the regression line. **B:** Plot of NORM-MARES concordance with line of perfect concordance provided for reference.

A



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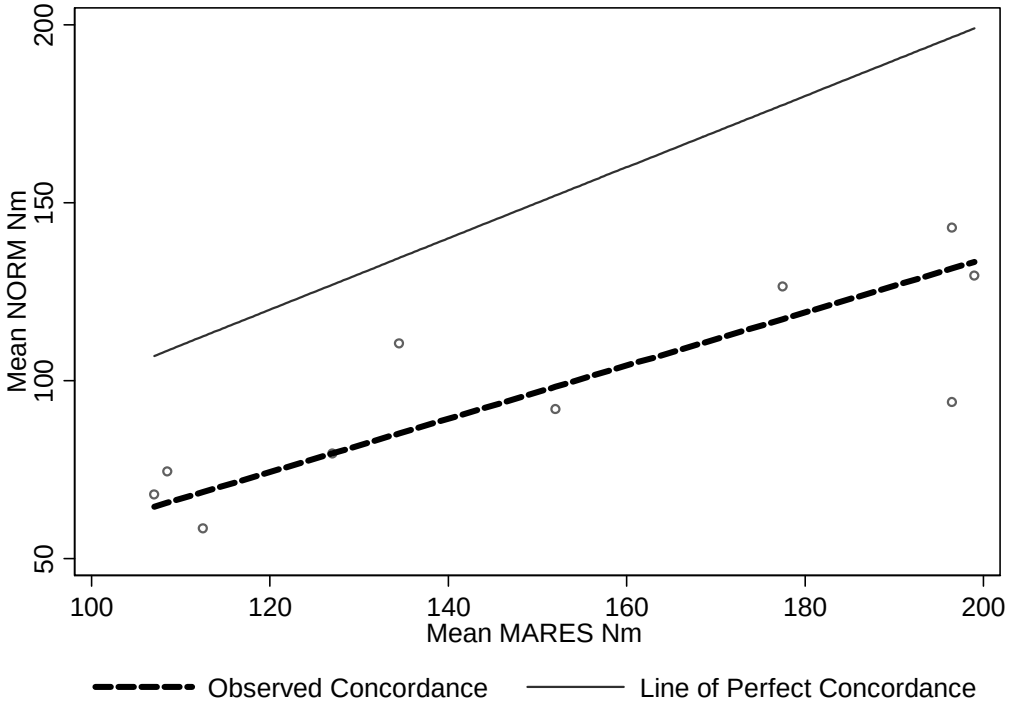

Figure 2. A: Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for $\mathbf{KF_{PkT}60}$. The thin dashed line represents the regression line. **B:** Plot of NORM-MARES concordance with line of perfect concordance provided for reference.

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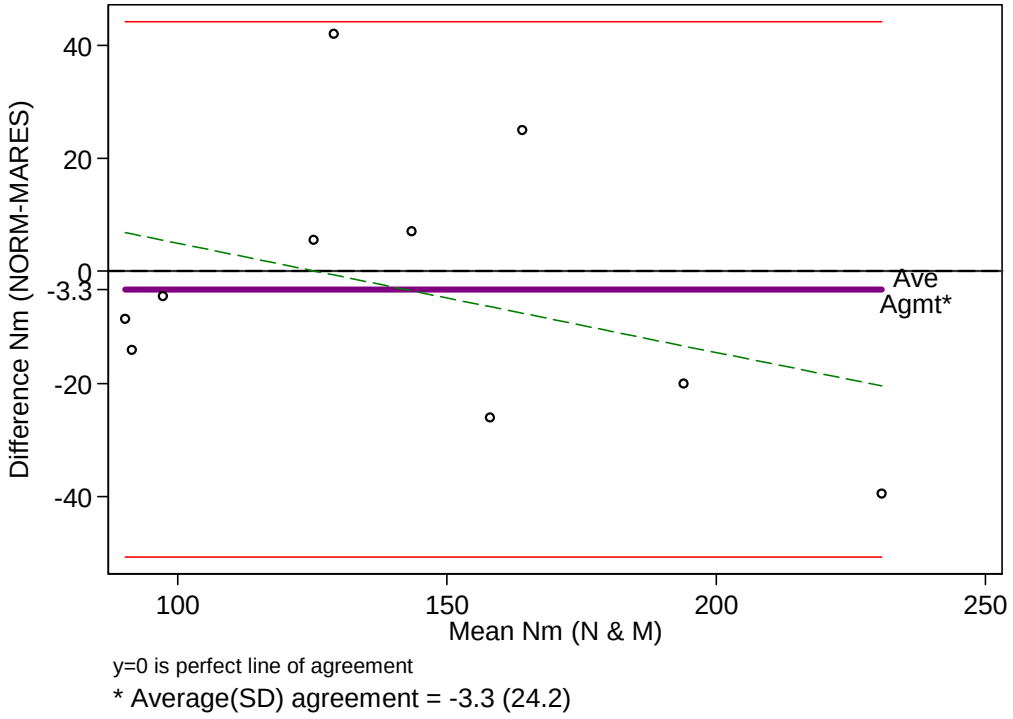

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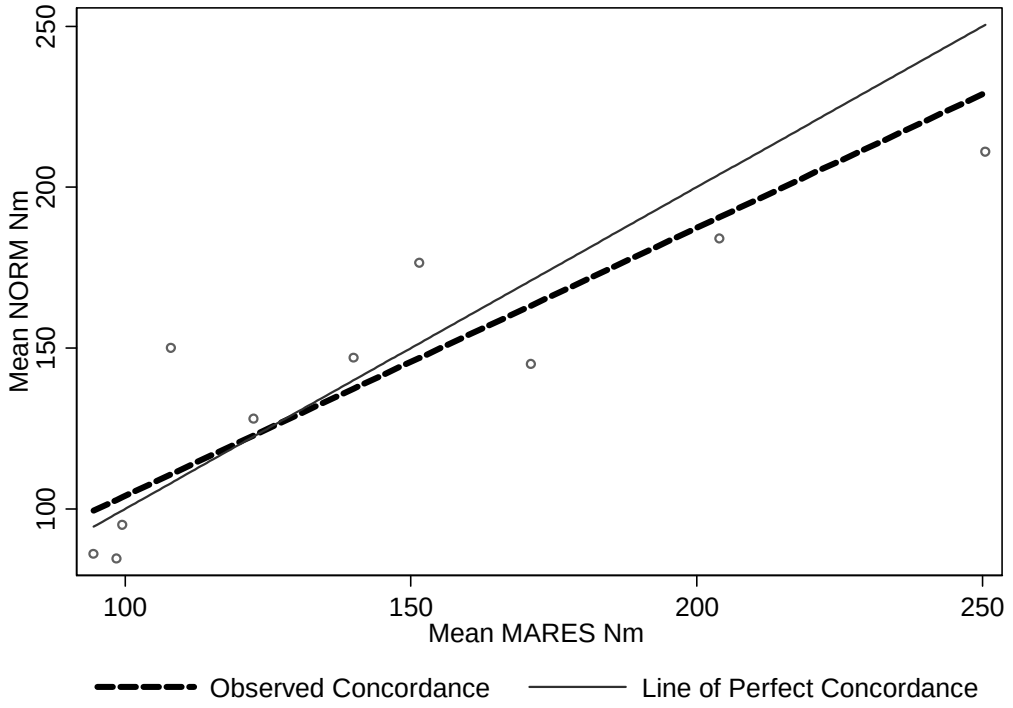
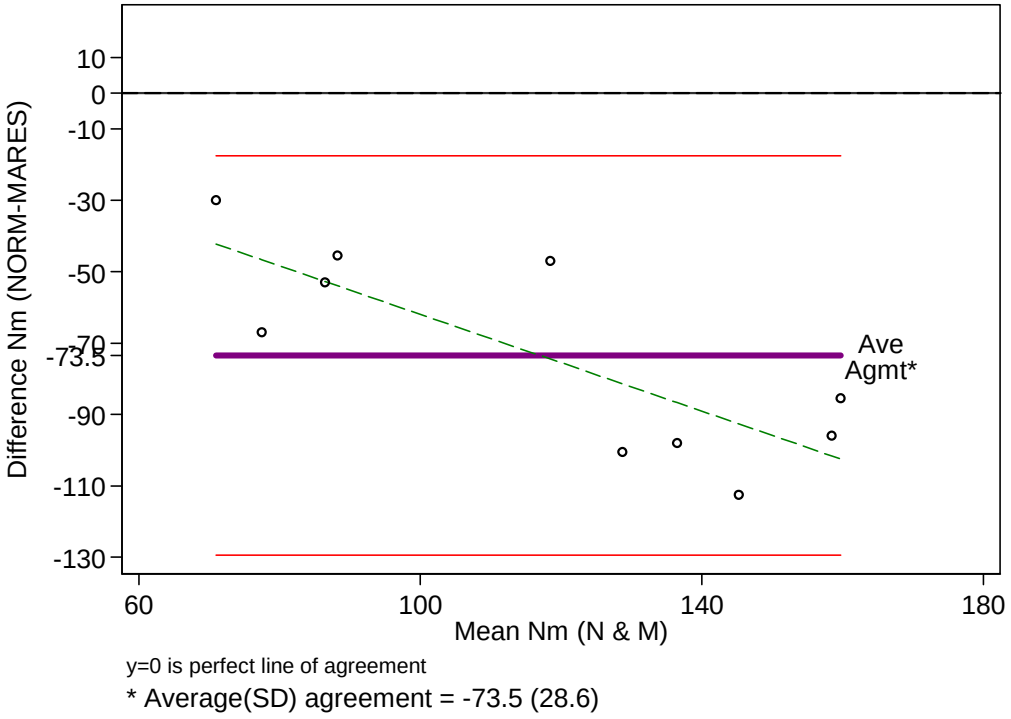


Figure 3. A: Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for **KE_{PkT}180**. The thin dashed line represents the regression line. **B:** Plot of NORM-MARES concordance with line of perfect concordance provided for reference.

A



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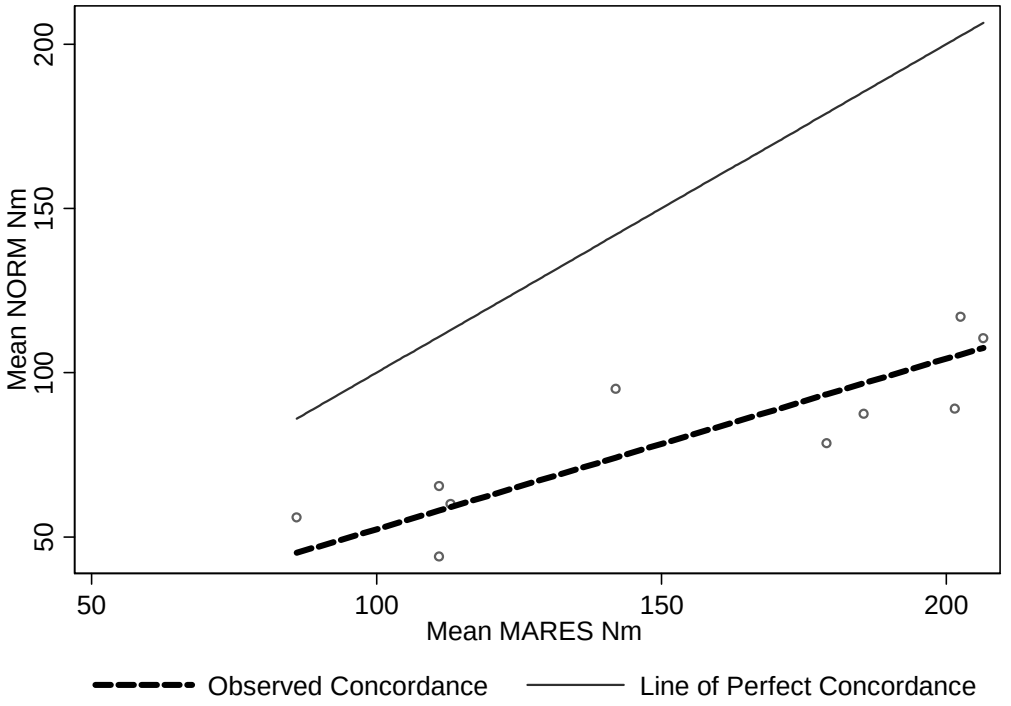

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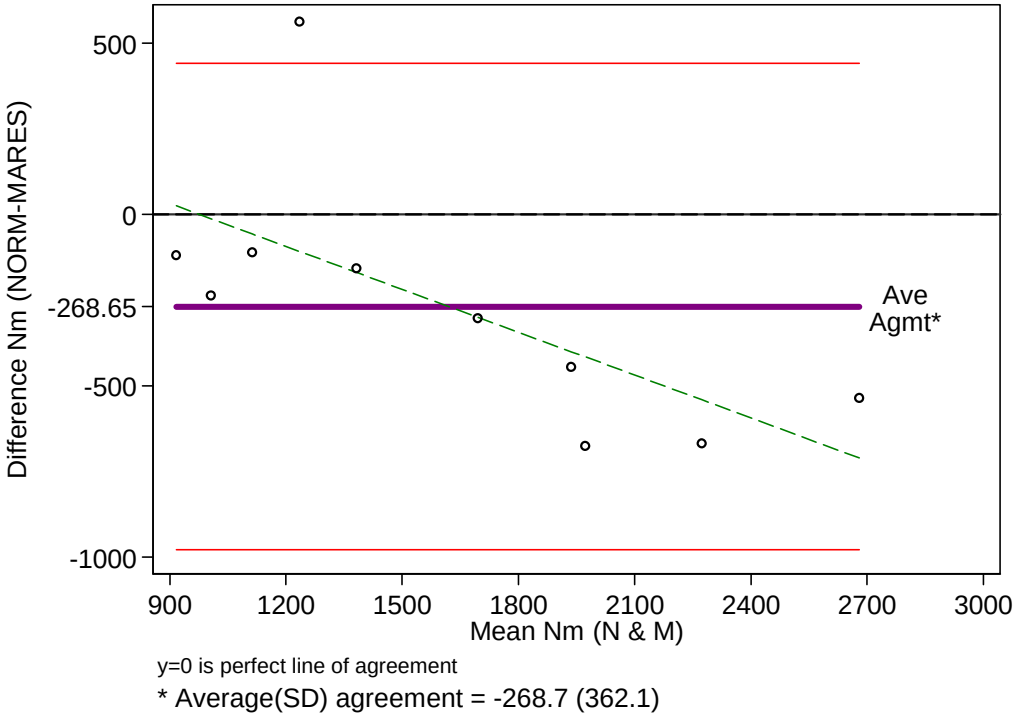

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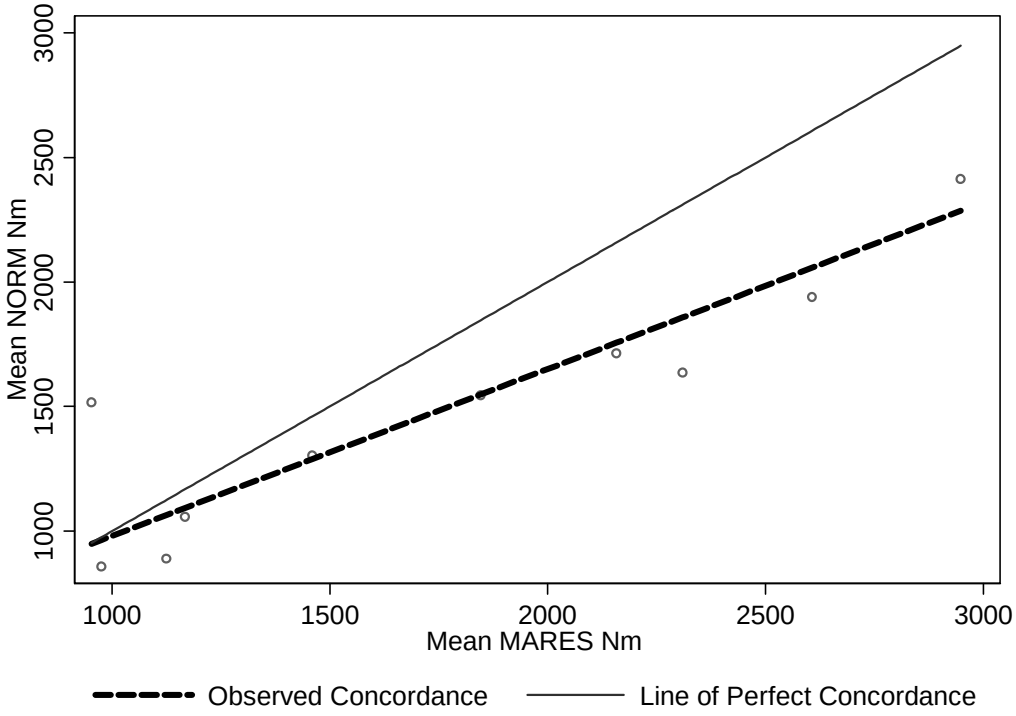

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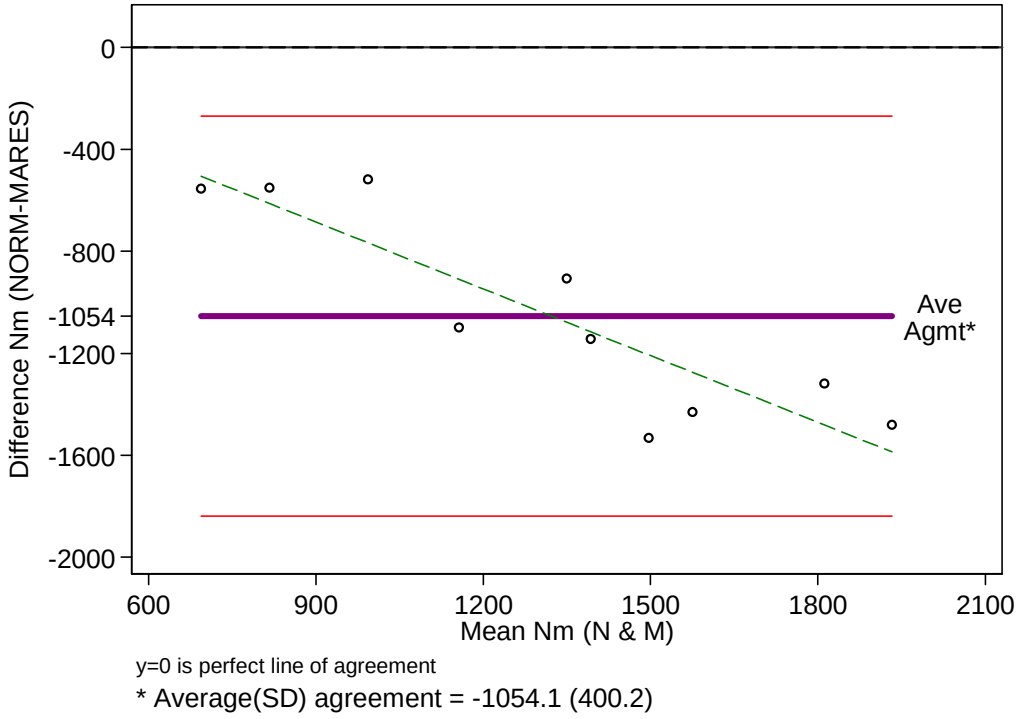

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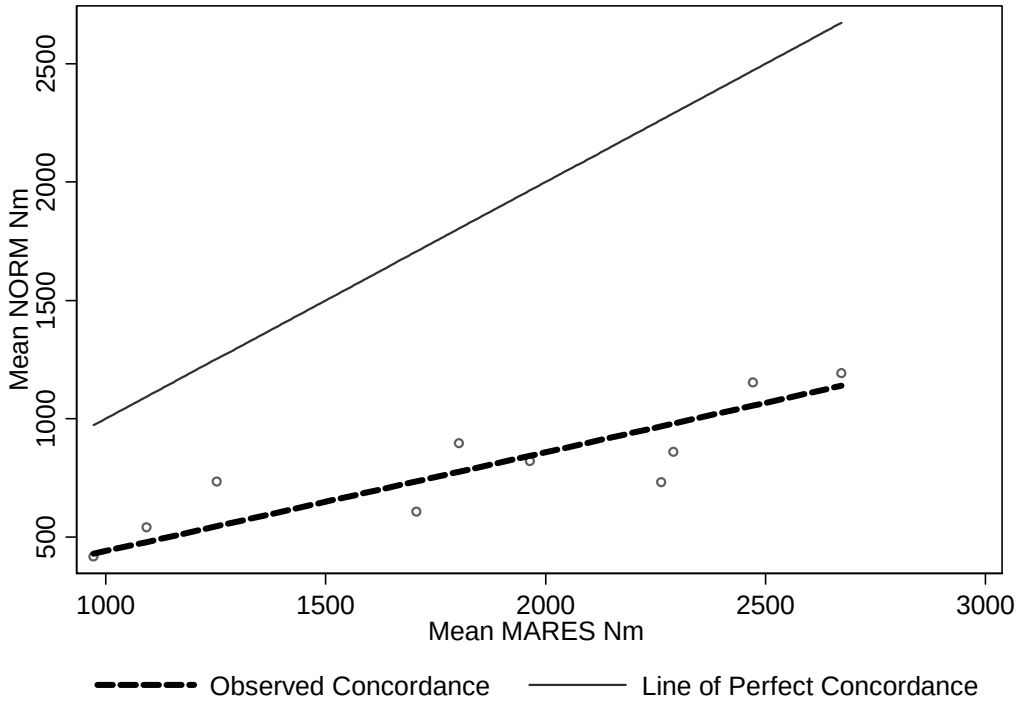

Figure 6. **A:** Bland-Altman plot depicting average agreement (bold solid line) between NORM and MARES with 95% limits of agreement (thin solid lines) for **KF_{TW}180**. The thin dashed line represents the regression line. **B:** Plot of NORM-MARES concordance with line of perfect concordance provided for reference.

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13. ABSTRACT *(Maximum 200 words)*

Introduction: ISS crew members perform pre- and post-flight testing to assess changes in muscle strength associated with long-duration exposure to microgravity. Currently no reliable, standardized inflight strength data exist. An understanding of the timeline of strength changes during long-duration space flight will facilitate improved exercise prescription and enhance countermeasures evaluation. The aims of this investigation were to: 1) evaluate the test-retest reliability of a proprietary dynamometer, and 2) determine its agreement with a standard, commercially available isokinetic dynamometer used for pre- and post-flight medical assessment testing. Methods: Six males and 4 females completed 2 sessions on a standard, commercially available isokinetic dynamometer (NORM) and 2 sessions on the Muscle Atrophy Research and Exercise System (MARES) in a random, counterbalanced order. Peak torque values at 60° and 180° • s-1 were obtained from 5 maximal repetitions of knee extension (KE) and knee flexion (KF). Total work at 180° • s-1 was determined from the area under the torque versus displacement curve during 20 maximal repetitions of KE and KF. Results: Intraclass correlation coefficients were relatively high for both devices (0.90 to 0.99). However, ratios of the within-device standard deviation were 1.3 to 4.3 times higher on MARES. Only one dependent measure, KE peak torque at 60° • s-1, exhibited good concordance between devices (rho = 0.91) and a small average difference (8.8 ± 16.7 Nm). Conclusion: MARES demonstrated acceptable test-retest reliability. However, due to poor agreement with NORM, it is not advisable to compare values obtained on these devices, e.g., to perform ground-based testing using NORM and inflight testing with MARES.

14. SUBJECT TERMS
MARES, muscle atrophy, knee flexion, knee extension, long-duration, inflight strength data

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