Reliability and Validity of the Multiaxis Profile Dynamometer with Younger and Older Participants

Curt B. Irwin, PhD
Trace Center, University of Wisconsin—Madison, Wisconsin

Mary E. Sesto, PT, PhD
Department of Orthopedics and Rehabilitation, University of Wisconsin—Madison, Wisconsin

The simple measurement of grip strength has been administered for many years with a wide variety of instruments and for very different purposes. The most widely used devices are those that quantify scalar magnitudes for strength (e.g., Jamar: J.A. Preston Corporation, Jackson, MI; and Baseline dynamometer: Fabrication Enterprises Inc., White Plains, NY). Grip strength devices, such as the Jamar and Baseline dynamometers, which are equivalent, and therefore, interchangeable for measurement of grip strength, have been used extensively in studies ranging from normative to those assessing function of the hand and the individual. These devices have been examined for test–retest reliability and have been used to validate other instruments. Their reliabilities have also been tested in different populations, ranging from children to older adults and has consistently demonstrated intraclass correlation coefficients (ICCs) greater than 0.90.

Another device commonly used to measure grip strength is the vigorimeter. This device measures grip strength (pressure) when squeezing a rubber bulb. Although the reliability (ICC: 0.84–0.86) of this instrument has been studied, this type of device has been criticized as being highly dependent on the hand–device interface. The vigorimeter measures the pressure exerted by the whole hand and is, therefore, a fundamentally different measurement than the force measurement obtained by the Baseline dynamometer. As pressure is defined as force/area, any change in the hand–device interface, and therefore, the area, greatly influences the measurement. Nevertheless, previous research has demonstrated...
moderate to good correlation (0.60–0.90) between the vigorimeter and the Jamar.\textsuperscript{10,17}

As grip strength is demonstrated to be a very valuable clinical and research measurement for assessing upper-extremity function\textsuperscript{18,19} disability,\textsuperscript{20} complication,\textsuperscript{21,22} and mortality,\textsuperscript{20} it is of critical importance that grip force measurement instruments are not only repeatable but are also capable of quantifying relevant variables associated with grip. One relevant variable is the direction in which the grip forces are oriented, which necessitates the measurement of shear forces. Pinch strength research indicates the direction in which the finger orient force is altered because of aging,\textsuperscript{23} but grip force orientation information is lacking. Another variable is the rate at which grip forces are built up. It is well known that grip strength declines with age, especially after the age of 65 years.\textsuperscript{2} However, recent research in the lower extremities of older adults indicates that the ability to rapidly build up force is more predictive of function than strength alone.\textsuperscript{24} Additionally, pinch force variability has been shown to increase because of aging,\textsuperscript{25} but neither the force buildup rates nor the force variability during power grip have been studied in older adults’ hands. Other potentially important grip-related variables include time to fatigue and estimations of individual finger contributions.

As current clinical grip strength measurement instruments do not quantify most of these variables, we developed a multiaxis profile (MAP) grip force dynamometer. The MAP is able to quantify grip force vectors produced by the hand.\textsuperscript{26} This information allows force magnitudes and the direction in which the forces are oriented to be described. Traditional grip measurement devices measure force only in one direction, thereby ignoring shear forces. In addition, the new device is also able to measure grip force over time (C.B. Irwin and R.G. Radwin, unpublished data, 2009), which allows examination of grip force buildup rates, force variability, and time to fatigue. The purpose of this study was to evaluate the test–retest reliability and validity of the MAP dynamometer in two different populations and compare the MAP with the Baseline dynamometer and vigorimeter.

**MATERIALS AND METHODS**

**Subjects**

The study included 28 right hand dominant participants, 14 older (>65 yr) and 14 younger (<30 yr) adults. Both groups comprised of 10 females and four males. Demographic data are detailed in Table 1. All young participants were university students and were tested on campus. The older individuals were all community dwelling and were tested at a local senior center. Exclusion criteria included pain, presence of upper-extremity injury, or difficulty using hands during activity. Additional exclusion criteria included sensory or cognitive impairments. Participants were compensated for their time, and the experimental protocol was reviewed and approved by the University of Wisconsin—Madison Human Subjects Committee.

**Instrumentation**

Three grip strength measurement devices were used in this experiment. The Baseline dynamometer (Fabrication Enterprises Inc.) was tested because of its prevalence in research and clinical settings. A vigorimeter (Baseline Inc., White Plains, NY), which consists of an air-filled bulb and a pressure gauge, was tested as it is also a common instrument for grip strength testing, especially in people with hand pain or injury.\textsuperscript{27} These devices are depicted in Figure 1.

The MAP grip strength dynamometer used in the study was a three-beam design affixed with a 6.35-cm diameter cylindrical plastic cover. Other covers in varying shapes or sizes are available, but we chose to use a cylindrical cover because of its similarity in shape to most handrails and grab bars. The dynamometer is displayed in Figure 2. Although all participants grasped a fixed 6.35-cm diameter handle, the plastic covers were sized according to each participant’s hand length in an effort to ensure that an equal proportion of their fingers contacted each beam. The pieces can be thought of as slices of a pie (Figure 3). Participants with smaller hands grasped smaller pie slices, and those with larger hands grasped larger pie slices.

Forces produced by the hands were measured with strain gauges that were mounted in a manner to

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Gender</th>
<th>N</th>
<th>Mean (SD), yr</th>
<th>Mean (SD), cm</th>
<th>Mean (SD), kg</th>
<th>Mean (SD), cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Younger</td>
<td>Female</td>
<td>10</td>
<td>24.5 (3.7)</td>
<td>170.7 (7.6)</td>
<td>81.6 (32.0)</td>
<td>17.7 (1.0)</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>4</td>
<td>22.25 (3.9)</td>
<td>179.1 (6.1)</td>
<td>81.0 (10.4)</td>
<td>19.3 (0.9)</td>
</tr>
<tr>
<td>Older</td>
<td>Female</td>
<td>10</td>
<td>74 (7.7)</td>
<td>159.1 (9.1)</td>
<td>71.9 (11.1)</td>
<td>17.7 (0.8)</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>4</td>
<td>77.25 (6.4)</td>
<td>170.8 (2.5)</td>
<td>81.8 (17.4)</td>
<td>18.5 (0.4)</td>
</tr>
</tbody>
</table>

SD = standard deviation.
ensure that the force measured was independent of vertical point of force application. Therefore, force measurements are the same regardless of where the handle is grasped along the MAP’s long axis. Two sets of gauges are mounted on each instrumented beam so that each beam measured two orthogonal force vectors. These orthogonal vectors are resolved into one force vector per instrumented beam (distal and proximal). Thus, each instrumented beam measured a force vector with magnitude and angle. The two individual force vectors are, in turn, resolved into one overall grip force vector, which is representative of grip strength (Figure 4).

For the purposes of the analysis in this article, the overall grip force vector was used. The overall grip force vector is described with a magnitude and an angle (Figure 5). Custom software was developed to acquire and compile the grip force data. Grip data were collected at 1,000 Hz. The instrumentation is described in detail in C.B. Irwin and R.G. Radwin (unpublished data, 2009).

**Procedure**

Before testing, demographic data were collected. Data included age, height, weight, and living arrangement. Anthropometric data of hand length and breadth were also collected. Additionally, participants completed questionnaires that focused on self-reported function. Participants were seated, and the grip strength—testing posture recommended by the American Society of Hand Therapists was used.2 Participants were positioned with the shoulder abducted and neutrally rotated with the elbow at 90° flexion and the wrist and forearm in neutral. Both the Baseline dynamometer and the vigorimeter were held suspended by the participant. The MAP dynamometer rested on the participant’s thigh. The MAP is heavier than the other two devices, and holding it suspended would require a large grip force, solely to keep it from slipping out of the participant’s hand. The Baseline dynamometer was set at span 2, and bulb 3 was used with the vigorimeter. For the MAP dynamometer, the metacarpal—phalangeal joint was lined up with a landmark on the handle to ensure repeatability of the hand placement.

For all devices, participants were instructed as, “squeeze the handle as hard as you can and build up force as quickly as possible and hold for 5 seconds.” Participants were given verbal indication for when to
begin and end each exertion. Three repetitions were completed for each hand and each device for a total of nine exertions per hand. Participants were provided at least a 1-min break between exertions. Additionally, participants alternated their hands between exertions to minimize fatigue. For each hand and each session, the order of grip devices was randomized. All participants were retested between one and two weeks after the initial testing.

Data Analysis

Both the absolute peak measure of grip force and the average of the middle 3 seconds or “plateau” phase of the grasp event were calculated for each repetition using the MAP dynamometer (Figure 6). The absolute peak of the force curve is analogous to the peak forces that were collected using the Baseline dynamometer and the vigorimeter. From the MAP dynamometer, four distinct measurements of grip force were evaluated for repeatability: 1) the maximum of the three repetitions for peak force measurement (Peak_{max}); 2) the maximum of the three repetitions for the plateau measurement (Plateau_{max}); 3) the average of the three repetitions for the peak measurement (Peak_{avg}); and 4) the average of the three repetitions for the plateau measurement (Plateau_{avg}). In addition, the overall grip force vector angle and forces from each instrumented beam were examined for repeatability. For the Baseline dynamometer and the vigorimeter, the Peak_{max} and the Peak_{avg} were evaluated for repeatability.

Data analysis was completed using SPSS version 17 (SPSS Inc., Chicago, IL.). Two-way random-effects, single-measure reliability ICCs were calculated. Pearson correlation coefficients were used to evaluate concurrent validity between session 1 peak grip strength measures for all three devices. Repeated-measures analysis of variance (ANOVA) was used to evaluate differences among testing sessions and differences among measurement devices. ANOVA was used to evaluate the differences based on age and gender. Post hoc analysis was completed using the Bonferroni multiple pairwise comparison method. Differences were considered significant at the 0.05 level of significance.
RESULTS

Grip Force

Maximal grip force results (Peak$\text{max}$) on both days for both younger and older adults are displayed in Table 2. Session 1 grip forces for all devices were used to test whether significant differences existed between right hand grip forces for younger and older individuals as well as between males and females. Depending on the device, older adults’ grip forces averaged between 60% and 71% of young participants’ (p < 0.05), and females averaged between 70% and 77% of the force of males (p < 0.05). Similar results were obtained for both methods of calculating grip force with the Baseline and vigorimeter and all four methods of calculating grip force with the MAP.

Differences between the maximum grip strength score of the three repetitions (Peak$\text{max}$) and the average of the three repetitions (Peak$\text{avg}$) for all three devices were less than 6% (p < 0.05). The results from the Peak$\text{max}$ and Plateau$\text{max}$ grip force measurements with the MAP indicate that the plateau phase of the grip force profile averaged 73% of the peak.

Differences between Sessions

No differences (p > 0.05) were detected between session 1 and session 2 for any of the four grip force variables with the MAP dynamometer or the two grip force variables with the vigorimeter and Baseline dynamometer. For sessions 1 and 2, Peak$\text{max}$ force grip data are presented in Table 2. In addition, no differences (p > 0.05) were detected for the overall grip force vector angle and the grip forces from the proximal instrumented beams between session 1 and session 2 (Table 3).

Reliability

Intraclass correlation coefficients for the right hand ranged from 0.95 to 0.99 for all devices and measurement types (Peak$\text{max}$, Peak$\text{avg}$, Plateau$\text{max}$, and Plateau$\text{avg}$). For the left hand, ICCs ranged from 0.94 to 0.98. Using Munro’s$^{28}$ correlation classification scheme, in which scores of 0.5–0.69 are considered to have a moderate correlation, 0.7–0.89 have high correlation, and 0.9–1.0 have very high correlation; all devices and measurement types had “very high” correlations. The response stability and ICCs for right hand Peak$\text{max}$ are displayed in Table 4. ICCs for the measures of overall grip force vector angle and the forces from each instrumented beam were between 0.92 and 0.95, indicating very high reliability.

Concurrent Validity

A significant difference in grip strength measures was found between the MAP and Baseline dynamometers (p < 0.05). Pearson correlation coefficients for the three different grip strength measurement devices indicate that the MAP dynamometer had high correlations with both the Baseline dynamometer (0.88–0.90) and the vigorimeter (0.78–0.88). Correlations between the Baseline and the vigorimeter were also high (0.78–0.83). All three devices were significantly correlated with each other for both hands (p < 0.001).

DISCUSSION

Both the Baseline dynamometer and vigorimeter are common clinical instruments for measuring grip strength. However, the vigorimeter measures a
pressure, which is a fundamentally different measurement than those obtained with either the Baseline or the MAP dynamometers. Although both Baseline and MAP dynamometers measure force, the MAP dynamometer is also able to quantify shear forces and force directions. If both instruments were grasped with the same hand geometry, the MAP, which measures both normal and shear forces, would register a greater grip force because of vector summation. However, the results of this study indicate that the participants can produce more force with the Baseline dynamometer. When grasping the Baseline, the fingers are able to curl around the handles. Alternately, when grasping a cylinder (like the MAP), the fingers are more extended and in a less biomechanically friendly position. This results in the decreased magnitude of measured grip forces observed in this study.

In the present study, the MAP measures of peak force (Peak$_{\text{max}}$ or Peak$_{\text{avg}}$) and plateau force (Plateau$_{\text{max}}$ or Plateau$_{\text{avg}}$), all demonstrated very high reliability. The plateau phase of the grasp has been referred to as “sustained strength” in other publications. Although there is no consensus on whether peak or plateau (sustained) strength is used, both measures have been shown to be repeatable. In comparison, standard clinical instruments, such as the Jamar, Baseline, or vigorimeter, only measure the peak force of the exertion, and information on the plateau phase of grip is unavailable.

Another disagreement exists when considering whether to use the average grip force of two or three repetitions or the repetition with the greatest grip force for analysis. The results of the present study indicate that the repetition with the greatest peak force was significantly greater (~6%) than the average force of the three repetitions. This finding is consistent with that of Langerstrom and Nordgren, which showed that one-repetition maximums averaged 4–5% greater than the average of three repetitions. Both methods have demonstrated very high repeatability in the present study. Other studies have concurrently examined both methods and have also demonstrated the repeatabilities of both. These findings stress the importance of stating which method is used in the analysis, as both are valid and repeatable, but the difference in force is approximately 4–6%.

The MAP dynamometer examined in the present study has reliability and validity consistent with other devices currently used in clinical and research settings,

### TABLE 2. Peak$_{\text{max}}$ Grip Force Data

<table>
<thead>
<tr>
<th>Hand</th>
<th>Age Group</th>
<th>Device</th>
<th>Session 1</th>
<th>Session 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>Younger</td>
<td>MAP (N)</td>
<td>226.6 (38.8)</td>
<td>219.1 (37.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baseline (N)</td>
<td>141.0 (37.4)</td>
<td>145.6 (48.1)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>MAP (N)</td>
<td>183.8 (57.5)</td>
<td>182.3 (56.6)</td>
</tr>
<tr>
<td></td>
<td>Baseline (N)</td>
<td>397.6 (80.2)</td>
<td>384.7 (77.5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vigorimeter (kPa)</td>
<td>94.3 (20.0)</td>
<td>95.5 (18.6)</td>
<td></td>
</tr>
<tr>
<td>Right</td>
<td>Younger</td>
<td>MAP (N)</td>
<td>242.3 (51.1)</td>
<td>236.0 (45.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baseline (N)</td>
<td>153.6 (49.0)</td>
<td>155.7 (54.9)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>MAP (N)</td>
<td>197.9 (66.7)</td>
<td>195.8 (64.1)</td>
</tr>
<tr>
<td></td>
<td>Baseline (N)</td>
<td>354.9 (105.5)</td>
<td>350.8 (108.0)</td>
<td></td>
</tr>
</tbody>
</table>

SD = standard deviation.

### TABLE 3. Session 1 and 2 Data for Secondary Grip Measurements

<table>
<thead>
<tr>
<th>Variable</th>
<th>Session 1</th>
<th>Session 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall force angle, degrees</td>
<td>88.8 (16.3)</td>
<td>88.8 (13.9)</td>
</tr>
<tr>
<td>Proximal beam force, N</td>
<td>75.2 (37.4)</td>
<td>78.2 (38.3)</td>
</tr>
<tr>
<td>Distal beam force, N</td>
<td>142.9 (43.5)</td>
<td>138.9 (42.0)</td>
</tr>
</tbody>
</table>

SD = standard deviation.

### TABLE 4. Response Stability for the Right Hand

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Device</th>
<th>Cronbach’s Alpha</th>
<th>ICC</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>MAP</td>
<td>0.99</td>
<td>0.99</td>
<td>5.4 N</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>0.99</td>
<td>0.97</td>
<td>12.8 N</td>
</tr>
<tr>
<td></td>
<td>Vigorimeter</td>
<td>0.98</td>
<td>0.96</td>
<td>3.9 kPa</td>
</tr>
<tr>
<td>Older</td>
<td>MAP</td>
<td>0.99</td>
<td>0.99</td>
<td>4.3 N</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>0.98</td>
<td>0.96</td>
<td>13.4 N</td>
</tr>
<tr>
<td></td>
<td>Vigorimeter</td>
<td>0.99</td>
<td>0.98</td>
<td>2.4 kPa</td>
</tr>
<tr>
<td>Younger</td>
<td>MAP</td>
<td>0.99</td>
<td>0.97</td>
<td>5.5 N</td>
</tr>
<tr>
<td></td>
<td>Baseline</td>
<td>0.98</td>
<td>0.97</td>
<td>11.1 N</td>
</tr>
<tr>
<td></td>
<td>Vigorimeter</td>
<td>0.95</td>
<td>0.90</td>
<td>4.8 kPa</td>
</tr>
</tbody>
</table>

MAP = multiaxis profile; ICC = intraclass correlation coefficient; SEM = standard error of measurement.
when testing both young participants and community-dwelling older adults. This is important, as evidence indicates that the older adult population may have greater relative variability in grip force. In addition, similar differences in grip strength were observed between young participants and community-dwelling older adults regardless of the device. The benefit of the new device is that information about the way hands produce force can be obtained from each trial. The grip profile can be dissected to reveal information on grip force vectors, force buildup, peak force, plateau force, force variability, and time to reach fatigue.

Unlike the Baseline dynamometer, the MAP captures the force vectors involved in gripping. This information is important, because results from Amis indicate that shear forces are a sizable portion of the overall grip force. Devices that only measure the scalar magnitude are unable to quantify the shear forces involved in gripping. Additionally, the MAP dynamometer can estimate the finger contributions involved in the grip (C.B. Irwin and R.G. Radwin, unpublished data, 2009), which can help clinicians or researchers determine whether individual fingers are not contributing to the grip. As a whole, these data available from the MAP dynamometer have clinical and research importance. By understanding which components of grip strength are most affected, targeted interventions can be developed to address the specific deficits. The limitations of the MAP dynamometer include its current lack of commercial availability and the cost due to specialized fabrication and instrumentation techniques. However, the MAP provides a more comprehensive evaluation of the function of the hand than is available from standard devices.

CONCLUSION

In populations of both healthy older and younger participants, the MAP dynamometer had very high reliability and validity, similar to other devices currently used in clinical settings. Grip strength differences between healthy older and younger participants were similar regardless of the device. The additional information provided by this device, including grip force vectors and angles, estimated finger contribution, and force buildup, may provide valuable information to rehabilitation specialists, therapists, surgeons, and designers to enhance the function of the hand.

Acknowledgments

The contents of this article were developed under grant 1UL1RR025011 from the Clinical and Translational Science Award Program of the National Center for Research Resources, National Institutes of Health, and grant T32 AG000265 Women’s Health and Aging Research and Leadership Training Grant from the National Institute on Aging.

REFERENCES

JHT Read for Credit
Quiz: Article # 163

Record your answers on the Return Answer Form found on the tear-out coupon at the back of this issue or to complete online and use a credit card, go to JHTReadforCredit.com. There is only one best answer for each question.

#1. The MAP device used in the study
   a. has never been previously described
   b. uses the same mechanical principles as the Jamar Dynamometer
   c. is in common clinical use in the UK and Australia
   d. is not in common clinical use in the US

#2. According to the authors, the MAP has the following advantage over the two other devices used in the study
   a. its improved reliability
   b. its improved validity
   c. its vector analysis of the digital forces applied to the grip mechanism
   d. its ease of use

#3. One of the goals of the study was to
   a. improve our understanding of grip function as we age
   b. strongly recommend the clinical use of the MAP over the other 2 devices
   c. introduce the MAP to US hand therapists
   d. detail the specifications of the MAP

#4. Reliability was statistically analyzed using
   a. a Pearson Product Moment
   b. an ICC
   c. an ANOVA
   d. the Student T Test

#5. The authors suggest that the Jamar Dynamometer is not reliable in the clinic
   a. true
   b. false

When submitting to the HTCC for re-certification, please batch your JHT RFC certificates in groups of 3 or more to get full credit.