

Development, construct validity, and reproducibility of a mimetic sealed jar measuring the dynamics of opening

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Abstract

Measurement of the dynamic kinetics involved in opening a jar may enable health care professionals to understand and train individuals in optimal hand/grip mechanics. This technical note details the design, validity, and reproducibility testing of a mimetic jar capable of measuring the forces and moments and isolated digital forces applied to the lid of the jar. An ecological jar instrument was designed with a torque limiter to provide a natural opening mechanism while a six-axis load cell and force sensing resistors recorded the way individuals applied force to the jar and lid during opening of a sealed container. A total of 115 volunteers participated in a validation of the device and an additional 36 participated in repeatability testing. Compared with prior instruments, this mimetic jar provides more force data and a simulated opening experience – making this jar instrument unique. Future studies utilizing the jar designed herein may allow health care professionals to evaluate patients suffering from debilitating osteoarthritis, fibromyalgia or other neuromuscular conditions and offer improvement strategies.

Keywords

Jar opening, biomechanics, hand forces, ergonomics, human factors

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Introduction

Jar opening is a problematic daily activity for older adults and persons of many clinical populations.^{1–4} Those with osteoarthritis, rheumatism, or other neuromuscular conditions need to make accommodations to their hand kinetics to successfully open a jar without increasing symptomology. Unfortunately, little data exist to help clinicians suggest proper hand kinetics for these individuals.

Several laboratories have developed tools to measure the kinetics and kinematics of opening a jar.^{3,5–15} Chang et al.¹² studied the kinetics of the thumb during jar opening using a force and torque sensing steel jar-like cylinder. This study demonstrated thumb kinetics are influenced by grasp pattern during simulated jar opening, but was limited in that the apparatus did not provide information on all digits. It also contained only one lid force transducer, making it only capable of recording thumb forces. Similarly, Fowler et al.⁷ investigated the hand and finger torques and forces during jar opening,

and measured three-dimensional loads applied to the interphalangeal joints. However, it also was only able to measure one digit and did not attempt to simulate sealed-jar opening with a torque release. Several other devices have been developed with similar limitations – especially the inability to simulate opening of the jar with a torque release.^{2,3,6,7,9,12–14} Carse et al.¹⁵ attempted to mimic a real jar opening event including a torque release by adding tape to the jar lugs to add friction and simulate a vacuum seal. While this approach allowed for the experience of breaking a seal, the

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opening torque was not kept constant due to degradation of the tape as a result of repetitive testing. These jar instruments have demonstrated the measurement capabilities possible when measuring human jar opening events. However, none of these jar instruments included all of the following: six axes of total forces applied to the jar, multiple lid grip sensors, and a torque limiter to repeatedly simulate the dynamic jar opening event.

Thus, we developed a mimetic device to measure the kinetics of the hand during jar opening, including both grip forces and resultant forces applied to the entire jar (between both hands) in six degrees-of-freedom. The ecological validity of this device is unhindered by artificial appearance and maintains a natural person-object interface. The testing herein is intended to determine the instrument's function and measurement capability by having healthy participants perform a bench top experiment to determine the jar's validity and repeatability.

Methods

Design and fabrication

A jar device was designed and constructed utilizing an AMTI FS6-100 (AMTI, Watertown, MA, USA) six degree-of-freedom load cell to measure the forces and moments applied to the jar between the hands, as well as force sensing resistors within the lid to measure the grip forces (Figure 1). Force data were acquired at 500 Hz through a digital acquisition device (NI USB-6215, National Instruments, Austin, TX, USA) interfacing with LabVIEW (version 8.2, National Instruments, Austin, TX, USA). The force range/resolution of the load cell in the x and y -direction was $\pm 185/0.090$ N, while the z -direction was $\pm 445/0.362$ N (maximum experienced in study: 78 N). About the x and y directions, the load cell's moment range/resolution was $\pm 3.76/0.0018$ Nm; the z -direction was $\pm 4.70/0.0023$ Nm (maximum experienced in study: 2.6 Nm). A calibration curve was provided from the company for converting voltage into force/moments.

The coordinates pertaining to the forces (F_x , F_y , F_z) and moments (M_x , M_y , M_z) of the load cell are with respect to the non-dominant hand holding the base of the jar. In order to express the results anatomically, the z -axis (F_z) was always in the downward direction, and the x -axis (F_x) extended normal to the palm of the lid hand. The y -axis (F_y), for right-handed participants, directed towards the individual's body, while for left-handed participants it pointed away. This convention allows for positive moments, with respect to the non-dominant hand grasping the jar, about the x -axis (M_x) to be radial deviation and about the y -axis (M_z) to be supination. A negative moment about the z -axis (M_z)

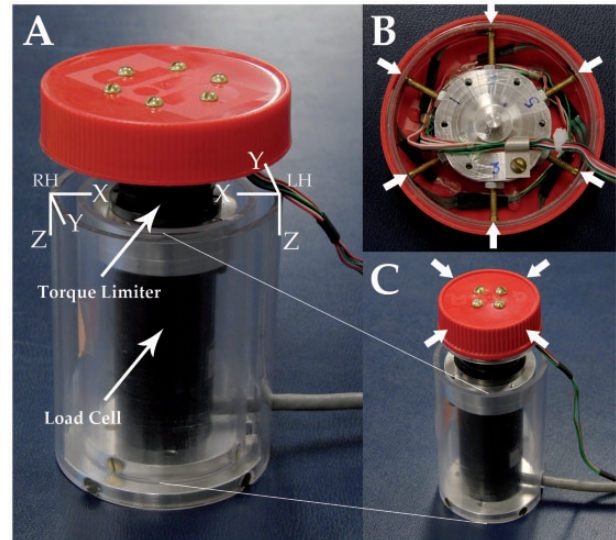


Figure 1. Force sensing jar with opening action. (a) Image of the large jar (83 mm \varnothing) with size and textural finish similar to a typical peanut butter jar. Arrow indicates six degrees-of-freedom load cell equipped with torque limiter set to 2.4 Nm. RH is the coordinate system used for right-handed participants and LH is the coordinate system used for left-handed participants. (b) Image of underside of the large jar lid. Arrows indicate positioning of FSR to record grip forces on lid. (c) Image of the smaller jar (55 mm \varnothing), which is contained within the large jar, utilizes the same load cell and torque limiter. The lid is interchangeable.

FSR: force sensing resistors; LH: left-handed; RH: right-handed

was in the direction of jar opening (counterclockwise). An illustration of the directionality of the forces (F_x , F_y , and F_z) is included (Figure 1).

This device utilized a torque limiter (R+W America, Bensenville, IL, USA; Model-SK1) set to 2.4 Nm and the jar lid opened freely at 45° to provide a similar experience to opening a real 'sealed' jar. Sealing the lid with a torque proportional to half the lid's diameter is a commonly used industry practice and thus we followed this principle when constructing the apparatus.¹⁶ The lid was equipped with compression force sensing resistors (FSRs) (Phidgets Inc., Calgary, AB, Canada) to measure the magnitude and direction of force application. These $\varnothing 5$ mm FSRs have a maximum force capacity of 100 N and resolution of 0.024 N (maximum experienced in study: 44 N). Each of the FSRs were individually calibrated by placing known weights over the sensor and developing individual equations to relate voltage to force. Grip force was calculated as the average of all sensors on the lid.¹⁷

The device was designed to accommodate two jar diameter sizes ($\varnothing 83$ mm and $\varnothing 55$ mm) with instrumented lids of matching dimensions and utilizes the same load cell and torque limiter. The large lid contained six sensors equally spaced radially, while the

small jar had four sensors. An 83 mm diameter jar was chosen because it is an optimally accessible jar lid diameter across sexes and anthropometrics and is representative of lids that are of a larger diameter.¹⁸ The smaller 55 mm diameter was chosen to highlight the smaller end of commercially available lid diameters. Both lids had a height of 20 mm because of its commonality. The lid height has been reported with little biomechanical consequences; however, the exact interaction between lid diameter and height has not been empirically studied.⁹

Validity and repeatability testing

This Institutional Review Board (IRB)-approved study (#0908M71484) enrolled 115 healthy volunteers (age: 24.5 ± 5.8 years; sex: 44 males/71 females; handedness: 105 right (R)/10 left (L)) to perform the jar opening task to define the range of forces applied to the large ($\text{\O}83$ mm) jar. All tests were performed during daytime hours in a classroom or laboratory setting housed within the same building with the same climate control parameters, however participants were not asked to clean hands prior to testing. The participants self-reported they were free from any hand, wrist, or other upper extremity pain. A test-retest study was then conducted on a different sample of 36 healthy consenting participants (age: 31 ± 9.5 ; sex: 6 males/30 females; hand dominance: 30 R/6 L) using the small ($\text{\O}55$ mm) jar set-up. Another cohort of 29 healthy consenting female participants (age: 25.4 ± 8.5 ; hand dominance: 26 R/3 L) were used to determine the repeatability of the large ($\text{\O}85$ mm) jar set-up.

Participants were instructed to grip the jar's base with their self-selected non-dominant hand, placing the center of their palm on top of a visual cue – the hand was positioned so that the x -direction extended normally to the palm. The participants were then told to grip the lid of the jar with their dominant hand in a manner most natural to them, without any influence, and turn the lid counterclockwise until the torque limiter released. The position of the lid FSRs with respect to the jar and load cell was consistent with FSR 1 positioned along the y -axis. While 'opening the jar', the

standing participant lifted the jar off the table and turned the lid one time until the torque limiter released.

Data were analyzed using a custom MATLAB (Mathworks Inc. Natick, MA, USA) script that measured all forces and moments up until the instant right before the torque limiter released – defined by a rapid decrease in M_z following the peak moment. The resultant direction and magnitude of grip force applied to the lid was computed using the data from the FSRs on the lid and their known position to determine components of the resultant vector.

Differences in forces and moments at peak M_z by sex and turning hand were tested via analysis of variance techniques for both jars. Between-participant variability was assessed with descriptive statistics for the large jar to display the range of values in this healthy sample. Repeatability of all forces and moments for both jar instruments was tested through use of intraclass correlation coefficient (ICC) and Pearson's r analysis. Alpha acceptance was 0.05 for all statistical tests.

Results

The healthy participants ($n = 115$) produced the opening torque consistently, but exhibited very different peak off-axis forces and moments. Large jar forces and moments applied to the jar were recorded at peak M_z are reported (Table 1). The standard deviation was 41% of the mean, on average for F_x , F_y , F_z , M_x , and M_y indicating both the variability in jar manipulation forces between participants and the ability of the jar device to measure these differences. There were no significant differences determined between males or females for any of the applied forces or moments to the jar or lid. Hand dominance revealed significant differences in axial force applied between right and left-handed, 28.8 ± 11.0 N versus 38.2 ± 20.0 N (F_z , $p = 0.019$), and the wrist radial deviation applied moment, 1.14 ± 0.43 N m versus 1.45 ± 0.42 N m (M_x , $p = 0.033$), when opening the jar.

The magnitude and direction of the final force vector was recorded for each participant and the average force magnitude was 9.61 ± 4.13 N at an angle of

Table 1. Summary statistics of forces and moments on large jar at the instant before opening ($n = 115$). Note the large standard deviations on the all channels except M_z demonstrate the inter-subject variability can be quite large in this healthy sample and that the jar instrument can measure these differences.

	F_x (N)	F_y (N)	F_z (N)	M_x (Nm)	M_y (Nm)	M_z (Nm)
Mean	-10.6	17.7	29.6	1.2	1.0	-2.4
Standard deviation	4.7	7.1	12.2	0.4	0.4	0.2

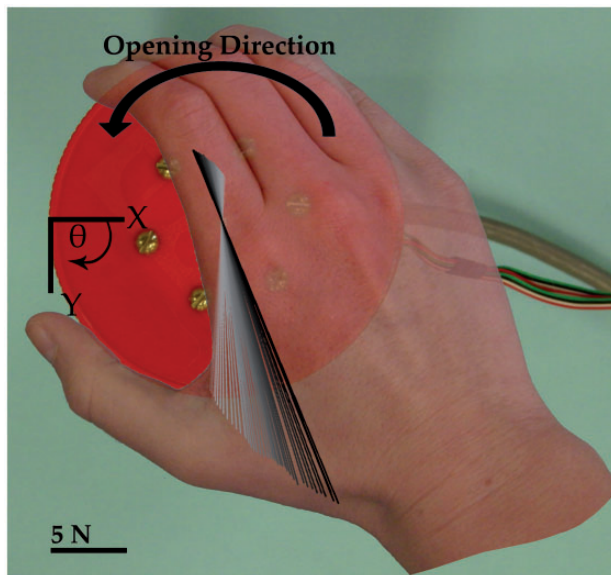


Figure 2. Grip force overlay on the hand/jar. Resultant grip force vectors are shown on the hand/large jar up to opening (black line) for representative data. Note the change in direction and magnitude of the vectors as sufficient torque is generated to open the jar. The scale bar indicates the length of 5 N.

84.88 ± 100.34 degrees. The orientation of large jar lid forces and direction, which depicts the grip force vectors leading up to jar opening where the longest and darkest vector represents that force immediately prior to opening, is included (Figure 2).

There was large variability in opening techniques. Two representative trials were selected showing an efficient and an inefficient opening of a jar (large lid), respectively (Figure 3). To open a jar, one must apply a torque and a downward axial force differentially between the lid and the jar; any additional torques and forces are unnecessary and inefficient. An example of an ideal opening, in that only the moment and force applied about the z -axis and in the z -direction respectively are prominent during the opening of the jar is included (Figure 3(a)). All other forces and moments are minimal. An example of an inefficient opening of a jar is presented (Figure 3(b)). This trial exemplifies an increased use of force and torque in the y -direction during the opening of the jar, which are not fundamentally necessary.

Verification of the reproducibility was performed using both the jar lids and a strong or very strong agreement between trials was observed for all forces and moments measured. A summary of the mean and standard deviation of the differences between the participant's trials, ICCs, and Pearson's correlation (r) values demonstrating the reproducibility of the experiments are included (Table 2).

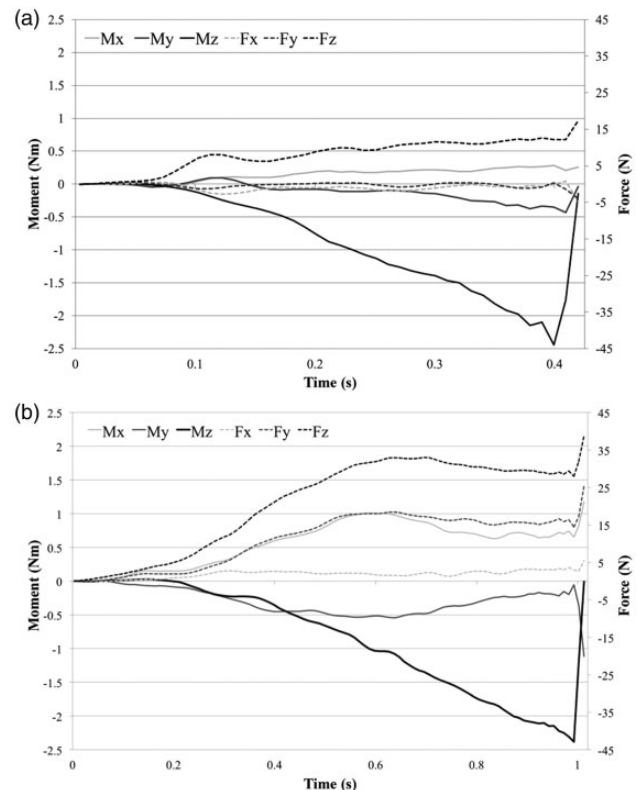


Figure 3. Force time history of large jar opening dynamics. The forces applied to the lid are shown as dashed lines and the moments about each axis are solid lines. (a) Illustrates a single trial for one individual with a biomechanically efficient jar opening technique. The torque required to open the jar (M_z) increases until opening and concurrent forces and moments are minimal. (b) An inefficient jar opening trial from one individual is shown here for comparison. Notice the large forces during this opening event which are not assistive in opening the jar. These additional and excessive forces indicate a less than optimal opening technique and demonstrate the potential for this device.

Discussion

This study involved the design and construction of an ecological jar with simulated and reproducible opening action, and the capability to measure both jar and lid forces and jar moments. The large and small jar instruments provided reproducible results for the load cell and grip forces between and within participants.

The participant trials showed several different large jar opening patterns and application of forces on the lid of the instrumented jar. The variance in the force and torque results between participants highlights the jar's potential to discern between different gripping patterns, indicating the jar could be used to study distinct gripping patterns and make clear the force and torque profiles for each gripping style. It also highlights an advantage of this jar instrument in that the result can be computed for each participant whereby enabling a

Table 2. Mean differences and standard deviation (SD) of sensor outputs, Pearson correlation coefficient (R ; p -value), and intraclass correlation coefficient (ICC; 95% CI) for between session scores of the small ($n = 36$) and large ($n = 29$) jar instrument. Force in Newton; moments in Newton meters.

	Small jar (55 mm Ø)			Large jar (83 mm Ø)		
	Mean diff. (SD)	Pearson r (p -value)	ICC (95% CI)	Mean diff. (SD)	Pearson r (p -value)	ICC (95% CI)
Grip	5.29 (4.00)	0.60 (<0.001)	0.75 (0.47–0.88)	5.75 (5.60)	0.88 (<0.001)	0.90 (0.78–0.94)
Normal Force (F_x)	0.226 (0.20)	0.66 (<0.001)	0.79 (0.56–0.90)	0.3 (5.3)	0.55 (<0.001)	0.72 (0.44–0.85)
Tangential (F_y)	0.044 (0.41)	0.61 (<0.001)	0.76 (0.49–0.88)	1.1 (5.3)	0.78 (<0.001)	0.85 (0.71–0.92)
Axial (F_z)	0.005 (0.95)	0.70 (<0.001)	0.82 (0.63–0.92)	0.5 (12.9)	0.61 (<0.001)	0.77 (0.55–0.88)
M_x	0.007 (0.005)	0.75 (<0.001)	0.86 (0.70–0.93)	0.1 (0.4)	0.54 (<0.001)	0.69 (0.39–0.84)
M_y	0.004 (0.003)	0.77 (<0.001)	0.87(0.72–0.94)	0.83 (0.4)	0.58 (<0.001)	0.73 (0.48–0.86)
M_z	0.01 (<0.001)	0.64 (<0.001)	0.78 (0.54–0.90)	0.01 (<0.001)	0.75 (<0.001)	0.86 (0.72–0.93)

CI: confidence interval; ICC: intraclass correlation coefficient; SD: standard deviation

more accurate picture of their gripping kinetics. This instrument also demonstrated good reproducibility within participants (Table 2). Thus, unlike its predecessors, this mimetic jar is able to measure both the six axes of forces between the hands repeatedly (ICCs from 0.69–0.90) and the grip forces on the lid under the hand during a simulated jar opening event.

The main limitation of this study is the placement of the force sensors in the lid of the jar did not directly align with the finger placement of the participants. Thus, the load applied by an individual finger could not be directly isolated using the current procedure. Additionally, the FSRs were not capable of measuring shear forces, only normal forces. There was also variance between the jar gripping styles of the participants that was not factored in to the determination of the mean direction of force on the lid. Therefore, future studies should be aimed at investigating the role of individual fingers in the jar opening activity and the categorization of grip style. Other factors that may play a role are environmental and personal factors such as humidity, sweaty palms, lotion, etc. Since this study was focused on validation and proof of concept, these likely had little or no influence on the results, but should be controlled in future studies aimed at quantifying and understanding inefficient opening strategies.

Future studies utilizing the described instrumented jar aim at detecting ineffective jar opening and gripping patterns of participants. Outcomes of these subsequent tests may help clinicians advise hand kinetics for individuals with neuromusculoskeletal conditions to maximize jar opening efficacy (diminish peak and sustained forces) and minimize pain during opening as well as investigate whether these clinical strategies alter opening kinematics. Potentially, with 3D kinematic measurements of the hand, inverse dynamics methods

could be used to estimate intra-articular forces within the hand. The evaluation of these intra-articular forces may expand our operational definition of ‘opening efficiency’ through the inclusion of factors that are intrinsic (i.e. joint forces) to the participant. This understanding may help in prescribing task modifications (e.g. joint protection) that temper risk factors known to contribute to the development or progression of conditions such as osteoarthritis. Altogether, this improved understanding of jar opening mechanics may improve individual’s function and independence.

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Declaration of conflicting interests

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