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Benchmarking Grasping and Manipulation: Properties of the Objects of Daily Living

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Abstract—**This paper presents a number of concepts related to benchmarking and evaluation of grasping and manipulation. A set of "Objects of Daily Living" based on a review of common domestic objects for manipulation as identified from sources in the literature is put forward, along with the physical properties of sample objects in those categories. Next, an experimental evaluation of the coefficient of static friction between these objects and a number of common household surfaces is performed. A key failure mode in unstructured object grasping occurs when the manipulator applies large contact forces that move the object out of grasp range. These results therefore give insight into the likelihood of a target object remaining in place to be successfully grasped in the presence of contact forces from the robot arm. This paper also presents a new classification of the Activities of Daily Living (ADLs), putting forth a standard categorization for the application of robotics in human environments. These topics and results have a number of uses related to benchmarking and performance evaluation in robotic manipulation, assistive technology, and prosthetics.**

I. Introduction

As robotic grasping and manipulation moves closer to practical implementation in human environments, it has become clear that quantitative metrics for evaluating performance in the presence of uncertainty must be developed. However, the large variability in the types and specifics of the grasping and manipulation tasks that can be performed by robots in domestic or workplace settings, as well as separating hardware performance from software-related factors (e.g. planning and control), makes creating absolute and translatable measures difficult.

This paper is the first in a series of planned papers related to benchmarking for grasping and manipulation and contributes to the topic in a number of ways. First, we create a new sub-classification of the Activities of Daily Living [1, 2] for the application of robotics in human environments, putting forth a standard categorization that allows robotic tasks to be discussed in terms of the analogous human tasks and their hierarchal classifications.

We then put forth an extensive list of "Objects of Daily Living", collected from key publications in the literature of the fields of robotics, prosthetics, and occupational therapy. These objects are categorized according to the most relevant Activities of Daily Living subcategory and the mass and dimensions of representative examples are given. This collection of common objects for grasping and manipulation in human environments can be referred to by researchers seeking to select a standard set of objects for testing and evaluation or a means of relating objects to a standard Activity of Daily Living category, and vice-versa.

Finally, we experimentally determine the amount of contact force required to displace those objects on a variety of common household surfaces. In unstructured human environments, the uncertainty inherent with imprecise sensing of unknown objects typically leads to a poor model of target object geometry and position/orientation. This poor object model leads to positioning errors of the robot manipulator arm and/or finger placements, which, in turn, can lead to large forces being inadvertently applied to the target object, potentially displacing it such that it is out of grasp range.

One measure of grasping performance in unstructured environments, therefore, is the magnitude of force applied to a target object during acquisition [3, 4]. If the horizontal component of this force exceeds the frictional force between the object and the surface it rests on, the object will be moved from its resting position, often causing the grasp attempt to fail. A table of experimentally-determined frictional properties for a large number of common objects and surfaces allows the researcher to predict whether target objects will move under certain grasping conditions, as well as a means to evaluate hardware, sensing, and/or algorithm performance. This information will also prove useful for simulation environments (e.g. [5-7]), as well as in developing grasp and planning databases [8], allowing for hardware designs and planning algorithms to be evaluated against a large number of target objects. A more precise estimate of the coefficient of static friction between an object and surface will add fidelity to simulation results, improving translation to real-world applications.

We begin this paper with a discussion of the Activities of Daily Living and the proposed sub-categorization. We then introduce the concept of "Objects of Daily Living", a collection of common household items associated with the Activities of Daily Living. We review the associated literature and put forth an extensive list of objects identified as common and/or important in domestic environments, including the physical proportions of common embodiments of the objects. Lastly, we present an experimental study in

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which we determine the frictional properties of these objects on a number of common household surfaces in order to lend insight into the likelihood of the objects being successfully grasped in the presence of the uncertainty inherent with manipulation in unstructured environments.

II. Activities and Objects of Daily Living

A. Activities of Daily Living

Many fields related to occupational therapy, rehabilitation, and gerontology use the term "Activities of Daily Living" (ADLs) in evaluating the ability of a patient to perform self-maintenance and other daily tasks crucial for unassisted living [1, 2, 9-13]. The term is generally used broadly and qualitatively. Many different sub-categories of the ADLs have been proposed to classify an individual's level of independence, including Physical Self-Maintenance (PSM) [9], Activities of Daily Living (ADLs) [1], Instrumental Activities of Daily Living (IADLs) [11, 12], and mobility [11], among others. These categorizations of the ADLs were developed to be used by a physician or occupational therapist to assist evaluation of human performance in daily tasks and determine, for instance, whether admission into a nursing home is justified for an elderly or disabled person.

Table I presents a new sub-classification of ADLs (drawn primarily from [10, 13]) designed for use with the application of robotics in domestic and work environments. These sub-categories are deemed "Domestic Activities of Daily Living (DADLs)", "Extradomestic Activities of Daily Living (EADLs)", and "Physical Self-Maintenance (PSM)".

The first and cardinal category, "Domestic Activities of Daily Living," contains subtasks spanning those regularly performed in human living environments. The majority of efforts related to assistive robotics focus on tasks in this category, particularly in Housekeeping and Food Preparation [14-16]. Typical approaches for assistance in this area consist as devices not intended to be utilized for tasks outside of this category. Exceptions, however, include work related to robotic wheelchairs and wheelchair-mounted manipulator arms (e.g. [17, 18]), which are frequently used outside of the home.

The second category, "Extradomestic Activities of Daily Living," contains activities and tasks performed primarily outside of the home. Note that housekeeping activities, technology use, and office tasks are classified primarily as DADLs, even though they are often performed as employment-related tasks. Aside from wheelchairs and related technologies, robotics applications for these areas include driver assists (e.g. [19]) and cooperative robots for manufacturing tasks (e.g. [20, 21]).

Assistance with tasks related to the final category, "Physical Self-Maintenance," is one of the most important areas of need in assisted-living and hospital environments. However, this application generally requires physical contact between the robot and human and is sufficiently challenging such that many tasks will not likely be tractable in the near future. Exceptions include Feeding/Medicating, which have been assisted by wheel-chair mounted arms, as well as robotic orthoses [22] and prosthetics (e.g. [23]) for assistance during Ambulation/Transfer.

TABLE I
Activities of Daily Living

Domestic Activities of Daily Living (DADLs)	
DADL1	Food Preparation
DADL2	Housekeeping
DADL3	Laundry
DADL4	Telephone/Computer/Technology Use
DADL5	Office Tasks/Writing
DADL6	Hobby/Sport
Extradomestic Activities of Daily Living (EADLs)	
EADL1	Transportation/Driving
EADL2	Shopping
EADL3	Employment-related Tasks/Tool Use
Physical Self-Maintenance (PSM)	
PSM1	Feeding/Medicating
PSM2	Toileting
PSM3	Bathing
PSM4	Dressing
PSM5	Grooming
PSM6	Ambulation/Transfer

B. Objects of Daily Living

Here we introduce the concept of "Objects of Daily Living," putting forth a collection of objects identified as important from a number of sources related to prosthetics, rehabilitation, and robotics. Among the included references, [24-28] are primarily from the occupational therapy literature and are related to evaluating human hand function in the context of objects that can be successfully grasped and utilized by individual patients. [29-31] relate to human hand grasp posture across the range of objects commonly utilized during manual tasks. [32, 33] are from the prosthetics literature, focusing on training amputees in the use of new prosthetic terminal devices as well as evaluating the performance of a device [34, 35]. Finally, [36, 37] relate to robotic grasping and manipulation.

A consolidated collection of "Objects of Daily Living" from these sources as well as a number of objects not found in the identified literature yet judged to be common and worthy of inclusion is presented in Appendix I. Due to the large variety of objects that humans interact with on a daily basis, exhaustively covering this space is not possible. Instead, by primarily working from objects regularly identified in the literature as important for grasping and manipulation, we seek to put forward a collection that would span the most commonly grasped and manipulated objects in domestic and work environments.

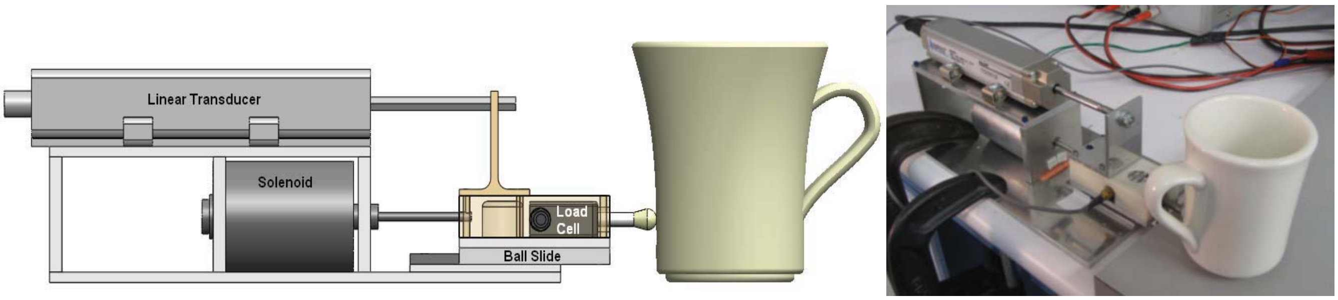

Fig. 1. Diagram of experimental apparatus with labeled subcomponents (left) and photograph of the apparatus during an experimental trial.

In the second column of the table, each object is related to up to three subcategories of the ADLs, as outlined in Table I. The sources identifying the object are listed in the third column. Objects without a source listed were not found in the identified literature yet were judged to be common objects worthy of inclusion. Objects fixed or partially fixed in space, such as door knobs and hand rails, are also not included. The content of the remaining columns is explained below.

III. Frictional Characteristics Evaluation

An experiment was performed to evaluate the level of force required to overcome the frictional force between the "Objects of Daily Living" identified above and various common surfaces found in human environments. This force information is used to calculate a coefficient of static friction for the object/surface pair – information useful for a number of applications related to evaluation of grasping and manipulation performance.

1) Experimental Setup and Procedure

The experimental apparatus consists of three main components: a push-style solenoid (Magnetic Sensor Systems S-29-200-H, 5 cm stroke), a pulsed-inductive linear transducer to measure probe travel (Balluff micropulse BIW-0075, 0.5 µm resolution), and a load cell to measure the contact force on the target objects (Transducer Techniques MDB-5, 22 N range). A ball slide mounted under the load cell is used as a linear bearing. The probe is tipped with a low-friction nylon sphere in order to minimize off-axis forces. A diagram and photo of the apparatus is shown in Fig. 1.

Six surfaces commonly found in human environments were tested: (birch) wood veneer, granite, furniture linoleum (a common surface used on desks, lab benches, and shelving, often called "laminate"), glass, unfinished wood, and stainless steel (Fig. 2). These surfaces are each shimmed to bring the center of the probe tip to 0.75 cm from the top of the test surface. Each of the objects (listed in Table III, in an appendix) was placed on surfaces resting on their most common "bottom".

Each experimental trial begins with the probe resting against the object while no current is being applied to the actuator. The tip is placed such that the direction of the applied force approximately goes through the center of support of the object (which is roughly the center of friction for most objects) such that the motion of the object after slip is pure translation [38]. Current is then applied at a rate of 0.05 amps/sec until the object begins to move. Contact force and tip displacement are measured via the load cell and linear transducer. The force applied to the object at the point of incipient slip is recorded and used to calculate the coefficient of static friction. Each object was tested five times.

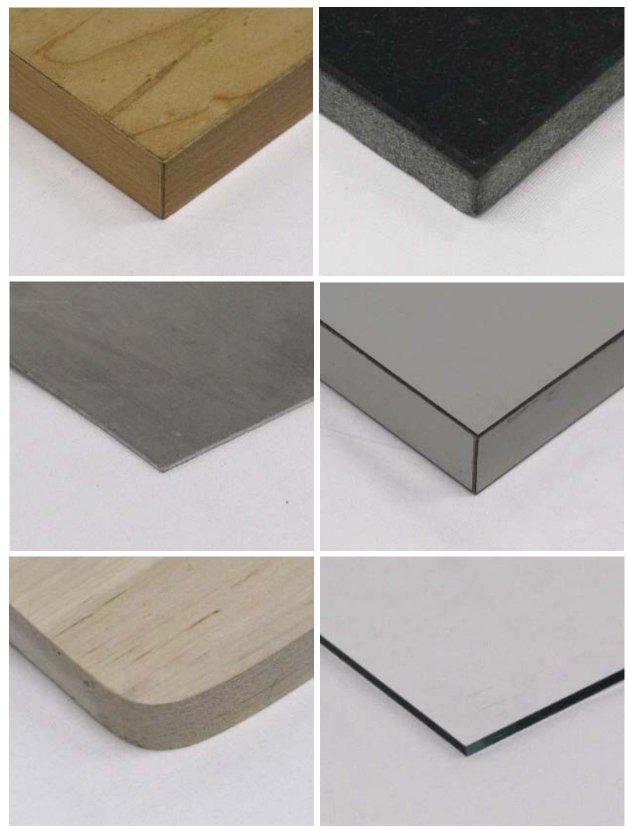

Fig. 2. Images of the six common surfaces tested: (from top left in clockwise order) birch wood veneer, granite, furniture linoleum, glass, unfinished wood, and stainless steel.

Fig. 3 shows data from a sample trial showing force (top) and displacement (bottom). The force at slip is taken as the point of the force curve where the force begins to decline after the steady incline (at approximately t=800). This point is followed directly by a series of stick-slip behaviors,

TABLE II
STATIC FRICTION COEFFICIENT RESULTS FOR SIX COMMON SURFACES

Object	Mass (g)	Veneer	Granite	Linoleum	Glass	Unfin. Wood	Stainless
ceramic mug, small	*351.1*	0.287±0.022	0.209±0.011	0.210±0.019	0.217±0.016	0.360±0.008	0.162±0.010
plastic bev. bottle (disp.)	26.1	0.245±0.042	0.324±0.031	0.197±0.027	0.255±0.028	0.326±0.032	0.304±0.030
wooden hair brush	*100.3*	0.404±0.046	0.342±0.018	0.317±0.031	0.250±0.031	0.570±0.047	0.251±0.021
metal stapler, rubber base	*423.1*	0.747±0.024	0.692±0.012	0.662±0.010	0.672±0.012	0.749±0.008	0.551±0.013
metal scissors, soft grips	*89.7*	0.402±0.063	0.384±0.020	0.288±0.031	0.328±0.029	0.420±0.030	0.307±0.025
aerosol spray can, steel	*360.2*	0.327±0.012	0.255±0.025	0.244±0.008	0.158±0.014	0.374±0.014	0.170±0.008
ink marker, plastic	*10.2*	0.338±0.063	0.157±0.041	0.431±0.066	0.324±0.040	0.431±0.059	0.309±0.028

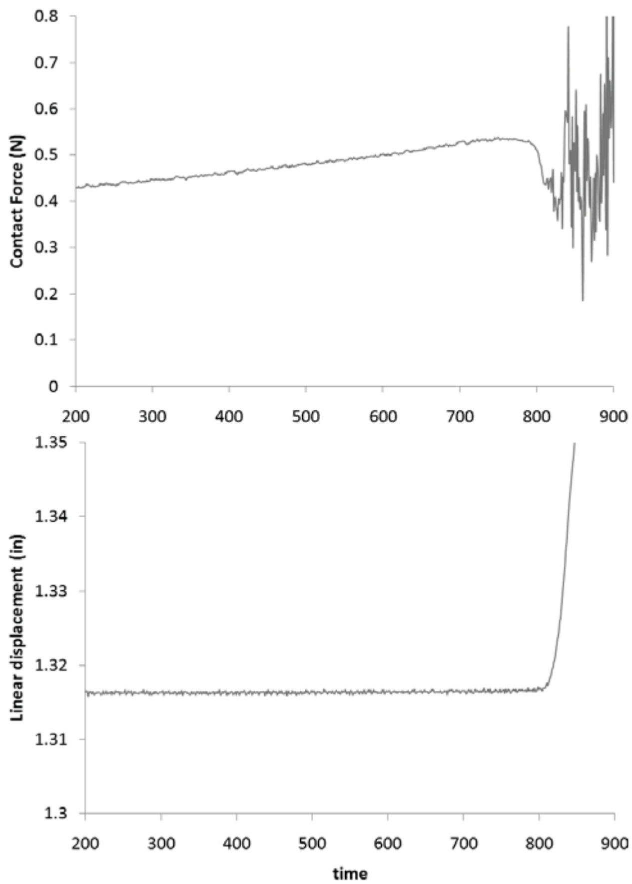

Fig. 3. Sample force (top) and displacement (bottom) plots from the friction force experiment.

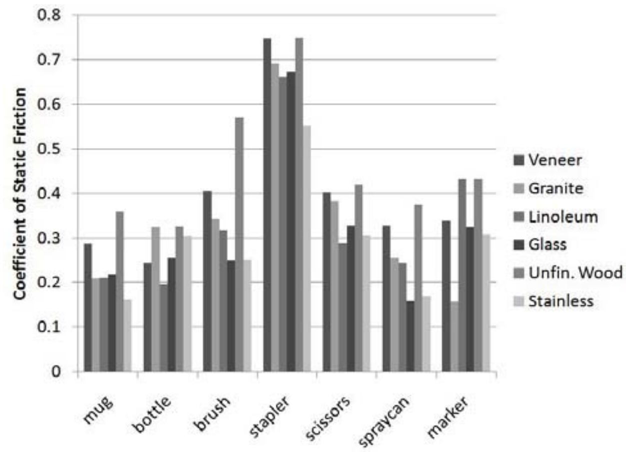

Fig. 4. Histogram of coefficient of friction for the seven objects tested on the full six surfaces.

clearly seen in the oscillations in the force trace.

For practical reasons, a number of the Objects of Daily Living were not able to be tested. Items that are soft and compliant (e.g. clothing), objects that would roll before sliding (e.g. sports balls), and objects not typically located on a table surface (e.g. a broom) were not tested. Additionally, objects with a resting height of less than 0.75 cm (e.g. coins, paper) were not tested as they would not be able to be appropriately contacted by the probe tip.

2) Results

Seven objects were tested on all six surfaces (wood veneer, granite, furniture linoleum, glass, unfinished wood, and stainless steel). These seven objects (small ceramic mug, disposable plastic beverage bottle, wooden hair brush, metal stapler with rubber base, scissors with soft grips, aerosol spray can, and ink marker) were chosen as a sampling of the full list, spanning a wide range of size, mass, and material. These results are shown in Table II and synthesized in Fig. 4. From this data, it can be seen that in general, the coefficients were most frequently between 0.2 and 0.3, although values as low as 0.15 and high as 0.75 were seen. Unsurprisingly, the stapler with the rubber base gave much higher values than any other object. Furthermore, the veneer and unfinished wood generally show the highest coefficients, with the other four surfaces generally lower.

In light of the lack of large variability in the coefficient of friction across the six surfaces, the full set of objects was tested on only three surfaces: veneer, granite, and furniture linoleum. These three surfaces were chosen based on their commonality in human environments as well as to span the range of frictional values while reducing the number of experimental trials required. The full results with the three representative surfaces are shown in Table III. In addition to a descriptive name of the object, the sources in the literature identifying (if any), the mass (in grams), and dimensions (in cm) of the tested object, this table provides the average measured coefficient of friction (displacement force divided by object mass) and standard deviation for the three surfaces. Note that for the dimensions given, objects were simplified as either boxes or cylinders: three values indicates the dimensions of a bounding box for the object (length x width x height) and two values indicates a cylindrical

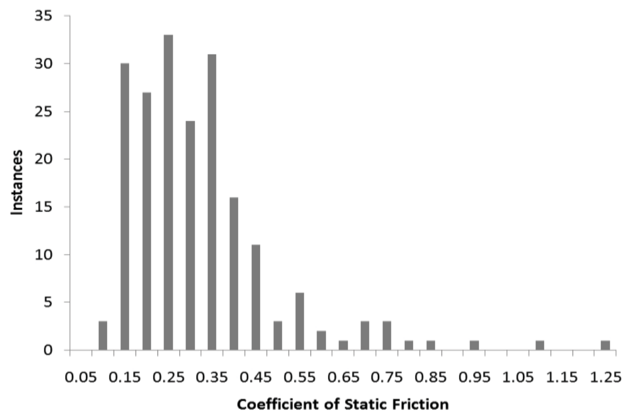

Fig. 5. Histogram of coefficient of static friction for the objects and surfaces tested.

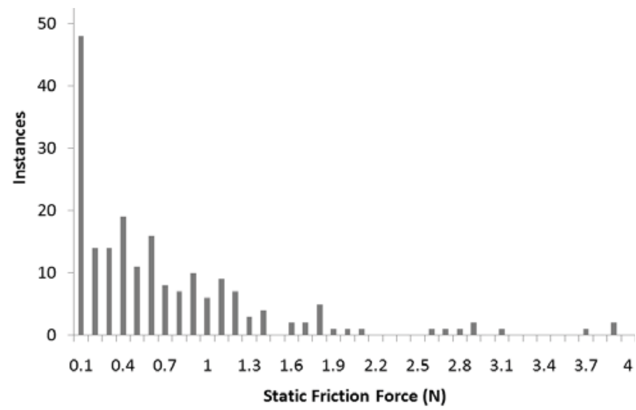

Fig. 6. Histogram of contact forces required to displace the objects given in Table II. Data from all three surfaces are included.

bounds (diameter x height). Fig. 5 shows the distribution of the coefficients of friction for this full trial, across the 65 objects and three surfaces tested.

DISCUSSION

These coefficient of friction data show an average of 0.300 and median of 0.255 across the 65 objects and 3 surfaces. While the values are heavily cluttered between 0.15 and 0.35, there is a large variation in coefficient of static friction across objects and surfaces. Unsurprisingly, objects with soft rubber grips such as the stapler and pliers, as well as the leather wallet have a much higher coefficient of friction across all surfaces. The objects with the smallest coefficients tended to be glass or other smooth materials.

Note that many of the objects tested are containers that might be empty or hold contents. We tested a number of these and found, unsurprisingly, that the coefficient of friction between the object and surface changes little as mass is added. Considering this, the object data given in Table III is for empty objects unless otherwise indicated. The frictional force for these objects with contents can then be extrapolated from the 'empty' condition.

In terms of benchmarking for robotic grasping, Fig. 6 shows a histogram of the maximum static friction force between the objects and the surfaces (i.e. the amount of force parallel to the surface required to displace the object). This data shows that the majority of object/surface pairs have a maximum static friction force below 1 N. More specifically, an average contact force of 0.463 N or less is required to avoid displacing 50% of the objects/surfaces tested, 0.116 N or less for 75%, and 0.051 N or less for 90% of the objects/surfaces tested. It is clear that a relatively small amount of contact force will displace the large majority of common objects on typical surfaces.

The results presented in this paper can be applied in a number of different ways. By putting forward a new classification of the Activities of Daily Living, robotic tasks can be discussed in terms of the analogous human tasks and their hierarchal classifications. The introduction of the Objects of Daily Living assists researchers seeking to select a standard set of objects for testing and evaluation for grasping and manipulation in human environments according to their application. Finally, the experimental data assists evaluation by lending insight into the likelihood of the objects being successfully grasped in the presence of uncertainty, where contact forces may be inadvertently large.

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REFERENCES

[1] Staff of the Benjamin Rose Hospital: "Multidisciplinary Studies of Illness in Aged Persons: II. A New Classification of Functional Status in Activities of Daily Living," J. of Chronic Diseases 9:55-62, 1959.

[2] S. Katz, A.B. Ford, R.W. Moskowitz, B.A. Jackson, M.W. Jaffe, "Studies of Illness in the Aged: The Index of ADL: A Standardized Measure of Biological and Psychosocial Function," Journal of the American Medical Association, vol. 185(12), pp.914-919, 1963.

[3] A.M. Dollar and R.D. Howe, "Simple, Robust Autonomous Grasping in Unstructured Environments," proceedings of the 2007 IEEE International Conference on Robotics and Automation (ICRA), Rome, Italy, April 10-14, 2007.

[4] A.M. Dollar, L.P. Jentoft, J.H. Gao, and R.D. Howe, "Contact Sensing and Grasping Performance of Compliant Hands," Autonomous Robots, special issue on Mobile Manipulation, 2009.

[5] A.T. Miller and P.K. Allen, "GraspIt!: A versatile simulator for grasping analysis," In Proc. of the ASME Dynamic Systems and Control Division, volume 2, pages 1251-1258, 2000.

[6] A. M. Dollar and R. D. Howe, "Towards grasping in unstructured environments: Grasper compliance and configuration optimization," Advanced Robotics, vol. 19 (5), pp. 523-544, 2005.

[7] A.M. Dollar and R. D. Howe, "Joint Coupling Design of Underactuated Grippers," Proceedings the 30th Annual ASME Mechanisms and Robotics Conference, 2006 International Design Engineering Technical Conferences (IDETC), Philadelphia, PA, Sept. 10-13, 2006.

[8] C. Goldfeder, M. Ciocarlie, H. Dang, and P.K. Allen. "The Columbia Grasp Database". In Proc. of the IEEE Int. Conf. on Robotics and Automation, 2009.

[9] M.F. Lowenthal, *Lives in Distress*, Basic Books, NY, 1964.

[10] M. Powell Lawton and E.M. Brody, "Assessment of Older People: Self-Maintaining and Instrumental Activities of Daily Living," Gerontologist, vol. 9(3), pp. 179-186, 1969.
[11] S. Katz, "Assessing Self-maintenance: Activities of Daily Living, Mobility, and Instrumental Activities of Daily Living," Journal of the American Geriatrics Society, vol. 31(12), pp. 721-727, 1983.
[12] W.D. Spector, S. Katz, J.B. Murphy, and J.P. Fulton, "The Hierarchical Relationship between Activities of Daily Living and Instrumental Activities of Daily Living," Journal of Chronic Diseases, vol. 40(6), pp. 481-489, 1987.
[13] D. Galasko et al., "An Inventory to Assess Activities of Daily Living for Clinical Trials in Alzheimer's Disease," Alzheimer Disease and Associated Disorders, vol. 11, supplement 2, pp. S33-S39, 1997.
[14] A. Saxena, J. Driemeyer, and A.Y. Ng, "Robotic Grasping of Novel Objects using Vision," International Journal of Robotics Research, vol. 27(2), pp. 157-173, 2008.
[15] S. Srinivasa, D. Ferguson, M. Weghe, R. Diankov, D. Berenson, C. Helfrich, and H. Strasdat, "The Robotic Busboy: Steps Towards Developing a Mobile Robotic Home Assistant," in International Conference on Intelligent Autonomous Systems, 2008.
[16] H. Nguyen, A. Jain, C. Anderson, and C.C. Kemp, "A Clickable World: Behavior Selection Through Pointing and Context for Mobile Manipulation," in Proc. IEEE/RJS International Conference on Intelligent Robots and Systems (IROS), 2008.
[17] H.A. Yanco, "Integrating Robotic Research: A Survey of Robotic Wheelchair Development," AAAI Spring Symposium on Integrating Robotic Research, Stanford University, CA, 1998.
[18] R. M. Alqasemi, E. McCaffrey, K. Edwards, and R. Dubey, "Analysis, evaluation and development of wheelchair-mounted robotics arms," in Proceedings of IEEE International Conference on Rehabilitation Robotics, pp. 469–472, 2005.
[19] C. Urmson et al., "Autonomous Driving in Urban Environments: Boss and the DARPA Urban Challenge," Journal of Field Robotics, 2008.
[20] M.A. Peshkin, J E. Colgate, W. Wannasuphoprasit, C.A. Moore, B. Gillespie, and P. Akella, "Cobot architecture," IEEE Transactions on Robotics and Automation, vol. 17, pp. 377–390, 2001.
[21] D. Shin, I. Sardellitti, and O. Khatib, "A Hybrid Actuation Approach for Human-Friendly Robot Design," Proc. of the IEEE International Conference on Robotics and Automation, Pasadena, CA, 2008.
[22] A.M. Dollar and H. Herr, "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State of the Art," IEEE Transactions on Robotics, special issue on Biorobotics, vol. 24(1), pp. 144-158, 2008.
[23] S.K. Au, M. Berniker, and H. Herr, "Powered ankle-foot prosthesis to assist level-ground and stair-descent gaits," Neural Networks vol. 21, pp.654-666, 2008.
[24] R.H. Jebsen, N. Talyor, R.B. Trieschmann, M.J. Trotter, and L.A. Howard, "An Objective and Standardized Test of Hand Function," Arch. Phys. Med. and Rehab., vol. 50(6), pp. 311-319, 1969.
[25] B. Kopp, et al., "The Arm Motor Ability Test: Reliability, Validity, and Sensitivity to Change of an Instrument for Assessing Disabilities in Activities of Daily Living," Archives of Physical Medicine and Rehabilitation, vol. 78, pp. 615-620, 1997.
[26] M.S. Rice, C. Laonard, M. Carter, "Grip Strengths and Required Forces in Accessing Everyday Containers in a Normal Population," Amer. Journal of Occup. Therapy, vol. 52(8), pp. 621-626, 1998.
[27] N. Smaby et al., "Identification of key pinch forces required to complete functional tasks," Journal of Rehabilitation Research and Development, vol. 41(2), pp. 215-224, 2004.
[28] Y.S. Choi, T. Deyle, T. Chen, J.D. Glass, and C.C. Kemp, "A List of Household Objects for Robotic Retrieval Prioritized by People with ALS," Proceedings of the IEEE International Conference on Rehabilitation Robotics, pp. 510-517, 2009.
[29] M.R. Cutkosky, *Robotic Grasping and Fine Manipulation*, 1985.
[30] T. Iberall, "Human Prehension and Dexterous Robot Hands," Intl. Journal of Robotics Research, vol. 16(3), pp. 285-299, 1997.
[31] M. Moussa, "Categorizing arbitrarily shaped objects based on grasping configurations," Robotics and Autonomous Systems, vol. 54, pp. 858-863, 2006.
[32] H. Jampol and J. Leavy "Training the Upper-extremity Amputee," in *Human Limbs and Their Substitutes*, Klopsteg and Wilson eds., Hafner Publishing, pp. 739-774, 1968.
[33] D.J. Atkins, "Adult Upper-Limb Prosthetic Training," in *Comprehensive Management of the Upper-Limb Amputee*, Springer-Verlag, pp. 39-59, 1989.
[34] C.M. Light, P.H. Chappell, P.J. Kyberd, "Establishing a Standardized Clinical Assessment Tool of Pathologic and Prosthetic Hand Function: Normative Data, Reliability, and Validity," Archives of Physical Medicine and Rehabilitation, vol. 83, pp. 776-783, 2002.
[35] S. Fishman, "The Principles of Artificial Limb Evaluation," in *Human Limbs and Their Substitutes*, Klopsteg and Wilson eds., Hafner Publishing, pp. 775-793, 1968.
[36] C.C. Kemp and A. Edsinger, "Robot Manipulation of Human Tools: Autonomous Detection and Control of Task Relevant Features," Proceedings of the 5th IEEE International Conference on Development and Learning: Special Session on Classifying Activities in Manual Tasks (ICDL5), 2006.
[37] A. Edsinger and C.C. Kemp, "Human-Robot Interaction for Cooperative Manipulation: Handing Objects to One Another," Proceedings of the 16th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), 2007.
[38] M.T. Mason and J.K. Salisbury Jr., *Robot Hands and the Mechanics of Manipulation*, MIT Press, 1985.

TABLE III
OBJECTS OF DAILY LIVING, ASSOCIATED ADLS, AND PHYSICAL PROPERTIES

Object	Categories	Source(s)	Mass (g)	Dims. (cm)	Veneer	Granite	Linoleum
Food Preparation							
bag of coffee beans, paper	D1, P1	[36]	n/a	n/a	n/a	n/a	n/a
baking pan (non-stick metal)	D1, P1, D2	[34]	351.9	21x11x8	0.105±0.006	0.139±0.013	0.069±0.007
bottle cap, metal	D1, P1, D2	[24, 31]	n/a	n/a	n/a	n/a	n/a
bowl, glass	D1, P1, D2	[28, 31]	545.1	18x8	0.223±0.009	0.124±0.006	0.163±0.003
box of crackers, cardboard	D1, P1	[37]	194.6	6x13x20	0.536±0.015	0.702±0.015	0.514±0.005
eating utensil, stainless steel	D1, P1, D2	*most sources	47.6	18x4x1	0.206±0.023	0.124±0.006	0.134±0.007
can of preserved food, steel	D1, P1		473.9	7x11	0.363±0.005	0.219±0.012	0.207±0.010
bowl, ceramic	D1, P1, D2	[28, 31]	479.3	13x8	0.236±0.006	0.111±0.009	0.266±0.011
juice carton (empty), paper	D1, P1, D2	[34]	74.5	10x10x24	0.257±0.011	0.303±0.040	0.252±0.013
coffee can (full), tin	D1, P1	[24]	397.4	10x18	0.329±0.016	0.163±0.008	0.219±0.016
dinner plate, ceramic	D1, P1, D2	[28]	798	27x3	0.350±0.011	0.222±0.004	0.349±0.011
drinking straw, plastic	D1, P1	[28]	n/a	n/a	n/a	n/a	n/a
beverage bottle, glass (empty)	D1, P1	[31, 32, 36]	213.7	6x24	0.325±0.030	0.171±0.020	0.168±0.018
beverage bottle, glass (full)	D1, P1	[31, 32, 36]	597.1	6x24	0.307±0.008	0.182±0.010	0.150±0.009
jar, glass	D1, P1, D2	[25, 34]	289	7x16	0.173±0.010	0.113±0.008	0.184±0.012
jar lid, steel	D1, P1, D2	[25, 30, 34]	n/a	n/a	n/a	n/a	n/a

TABLE III *continued*
OBJECTS OF DAILY LIVING, ASSOCIATED ADLS, AND PHYSICAL PROPERTIES

Object	Categories	Source(s)	Mass (g)	Dims. (cm)	Veneer	Granite	Linoleum
measuring cup, glass	D1, P1, D2		824	15x11	0.140±0.005	0.103±0.003	0.119±0.006
skillet, metal	D1, P1, D2		987.5	27x5	0.187±0.005	0.112±0.003	0.179±0.001
cup/glass, glass	D1, P1, D2	[28, 31, 33]	*402.3*	9x15	0.250±0.009	0.126±0.012	0.147±0.008
plastic container	D1, P1, D2	[28]	*44.8*	14x14x6	0.289±0.040	0.328±0.006	0.305±0.038
pitcher, plastic	D1, P1, D2	[31, 33, 34]	*292.7*	18x11x24	0.210±0.007	0.161±0.011	0.217±0.007
beverage bottle, disp. plastic	D1, P1	[28, 33]	*26.1*	7x22	0.245±0.042	0.324±0.031	0.197±0.027
cooking pot w/handle, steel	D1, P1, D2		503.6	17x10	0.238±0.002	0.124±0.007	0.173±0.007
salt/pepper shaker, glass	D1, P1	[33]	*235.1*	5x19	0.235±0.016	0.124±0.013	0.202±0.013
soda can (empty), tin	D1, P1	[28, 31]	*13.5*	7x12	0.307±0.038	0.248±0.036	0.285±0.028
mug, ceramic	D1, P1, D2	[25]	*351.1*	8x10	0.287±0.022	0.209±0.011	0.210±0.019
spatula, plastic	D1, P1, D2	[31]	*89.7*	33x5x2	0.297±0.009	0.310±0.012	0.290±0.018
tray	D1, P1, D2	[32-34]	*n/a*	n/a	n/a	n/a	n/a
water bottle, non-disp. plastic	D1, P1, D2	[28, 31]	*179.4*	9x20	0.212±0.010	0.099±0.004	0.269±0.024
wine bottle (empty), glass	D1, P1	[31]	482.3	8x30	0.222±0.012	0.164±0.007	0.141±0.010
wine bottle (full), glass	D1, P1	[31]	1247.4	8x30	0.216±0.005	0.142±0.006	0.135±0.004
wine glass, glass	D1, P1, D2	[31]	*268.3*	8x20	0.306±0.012	0.205±0.014	0.209±0.005
Housekeeping							
aerosol spray can, steel	D2, E3	[26]	360.6	7x20	0.327±0.012	0.255±0.025	0.244±0.008
broom	D2	[32, 33]	*n/a*	n/a	n/a	n/a	n/a
dust pan	D2	[33, 35]	*n/a*	n/a	n/a	n/a	n/a
electrical plug	D2, E3	[36]	*n/a*	n/a	n/a	n/a	n/a
lightbulb	D2, E3		*n/a*	n/a	n/a	n/a	n/a
small pillow	D2	[28]	*n/a*	n/a	n/a	n/a	n/a
spray bottle, plastic	D2, E3	[26]	633.7	12x7x27	0.135±0.006	0.193±0.008	0.166±0.005
vase, glass	D2	[31]	*1207.7*	119x35	0.173±0.005	0.084±0.004	0.161±0.005
Laundry							
shirt button	D3, P4	[34]	*n/a*	n/a	n/a	n/a	n/a
cardigan	D3, P4	[25]	*n/a*	n/a	n/a	n/a	n/a
coat hanger	D3, P4	[31]	*n/a*	n/a	n/a	n/a	n/a
hand towel	D3, P3	[28]	*n/a*	n/a	n/a	n/a	n/a
hat	D3, P4	[33]	*n/a*	n/a	n/a	n/a	n/a
clothes iron, plastic	D3	[31, 33]	*1179*	13x11x26	0.313±0.007	0.331±0.004	0.334±0.006
pants	D3, P4	[28, 33]	*n/a*	n/a	n/a	n/a	n/a
shirt	D3, P4	[28, 33]	n/a	n/a	n/a	n/a	n/a
socks	D3, P4	[28]	n/a	n/a	n/a	n/a	n/a
necktie	D3, P4	[32, 35]	n/a	n/a	n/a	n/a	n/a
Telephone/Computer/Technology Use							
cellular telephone, plastic	D4	[28]	*104.7*	9x5x3	0.377±0.002	0.195±0.013	0.291±0.022
remote control, plastic	D4	[28]	*149.7*	17x6x4	0.433±0.039	0.504±0.019	0.391±0.014
phone receiver, plastic	D4	[25,28,32,33]	*133*	17x4x3	0.204±0.016	0.137±0.018	0.202±0.018
DVD case, plastic	D4, D6		*107.5*	19x13x2	0.289±0.026	0.336±0.022	0.337±0.018
Office Tasks/Writing							
binder clip, steel	D5		8.7	4x3x3	0.310±0.047	0.270±0.039	0.339±0.031
Eraser, rubber	D5	[33]	*21.5*	6x3x1	0.644±0.021	0.591±0.028	0.751±0.052
marker, felt-tip, plastic	D5	[36]	*10.2*	1x14	0.338±0.063	0.157±0.041	0.431±0.066
paper clip, steel	D5	[24, 33]	*n/a*	n/a	n/a	n/a	n/a
paper envelope/mail	D5	[28, 33]	*n/a*	n/a	n/a	n/a	n/a
pen cap, plastic	D5	[30]	*n/a*	n/a	n/a	n/a	n/a
Pen, plastic	D5	[28,30,33,35]	*4.6*	1x15	0.315±0.045	0.283±0.097	0.348±0.030
ruler	D5	[33]	*n/a*	n/a	n/a	n/a	n/a
scissors, metal w/soft grips	D5	[28, 33, 36]	*89.7*	22x9x1	0.402±0.063	0.384±0.020	0.288±0.031
stapler, metal w/rubber base	D5		*423.1*	18x3x6	0.747±0.024	0.692±0.012	0.662±0.010

TABLE III *continued*

OBJECTS OF DAILY LIVING, ASSOCIATED ADLS, AND PHYSICAL PROPERTIES

Object	Categories	Source(s)	Mass (g)	Dims. (cm)	Veneer	Granite	Linoleum
Hobby/Sport							
camera, digital, plastic	D6, D4	[33]	*225.7*	10x3x7	0.241±0.026	0.146±0.015	0.352±0.007
card deck, paper	D6	[33, 35]	*97.2*	9x7x2	0.542±0.045	0.501±0.035	0.399±0.027
magazine	D6	[28]	*n/a*	n/a	n/a	n/a	n/a
newspaper	D6	[28]	*n/a*	n/a	n/a	n/a	n/a
book, paperback, paper	D6	[28]	*364.3*	20x13x2	0.371±0.005	0.387±0.007	0.497±0.015
Transportation/Driving							
Keys	E1, D2	[27,28,21-34]	*n/a*	n/a	n/a	n/a	n/a
umbrella, foldable, cloth	E1	[33]	*208.1*	5x23	0.209±0.006	0.272±0.009	0.253±0.002
Shopping							
coin	E2	[24, 28, 34]	*n/a*	n/a	n/a	n/a	n/a
credit card	E2	[28]	*n/a*	n/a	n/a	n/a	n/a
paper currency	E2	[28]	*n/a*	n/a	n/a	n/a	n/a
Tool Use/Employment-related Tasks							
hammer, wood handle	E3	[36]	*352.8*	30x3x2	0.243±0.007	0.128±0.012	0.196±0.008
hot glue gun, plastic	E3, D6	[36]	*217.6*	17x4x3	0.140±0.005	0.122±0.018	0.172±0.008
paintbrush, large, wood	E3	[36]	*126.3*	23x8x2	0.458±0.023	0.432±0.031	0.437±0.023
nut	E3	[30]	*n/a*	n/a	n/a	n/a	n/a
Pliers, rubber grip	E3	[36]	*150.4*	16x5x1	1.071±0.022	0.693±0.010	0.820±0.010
screw	E3	[34]	*n/a*	n/a	n/a	n/a	n/a
Screwdriver, plastic	E3	[35, 36]	*74.3*	2x20	0.362±0.052	0.211±0.008	0.389±0.013
Feeding/Medicating							
book of matches	P1, D2	[32, 33]	*n/a*	n/a	n/a	n/a	n/a
lighter, metal flip-top	P1, D2	[28, 31]	*57*	4x1x6	0.189±0.016	0.102±0.016	0.182±0.015
med. bottle (empty), plastic	P1	[26, 28]	*21.6*	4x7	0.306±0.023	0.310±0.043	0.280±0.051
medicine box, paper	P1	[28]	*19.7*	12x9x2	0.477±0.045	0.208±0.031	0.513±0.033
medicine pill	P1	[28]	*n/a*	n/a	n/a	n/a	n/a
syringe	P1	[30]	*n/a*	n/a	n/a	n/a	n/a
Bathing							
soap box, w/soap, paper		P3	[28]	*131.2*	9x7x4	0.316±0.032	0.370±0.029
toothbrush, plastic	P3	[31]	*16.4*	19x1x1	0.299±0.051	0.183±0.039	0.369±0.033
toothpaste tube, plastic	P3	[28, 33]	*191.4*	3x21	0.118±0.011	0.409±0.021	0.137±0.006
Dressing							
eyeglasses, plastic frame	P4	[28, 33]	*24.9*	14x3x3	0.233±0.030	0.255±0.020	0.265±0.027
purse/handbag	P4, E2	[28]	*n/a*	n/a	n/a	n/a	n/a
shoe(s)	P4	[28, 33]	*n/a*	n/a	n/a	n/a	n/a
shoelace	P4	[25]	*n/a*	n/a	n/a	n/a	n/a
wallet, leather	P4, E2	[28, 33]	*114.8*	11x9x3	0.930±0.027	1.238±0.059	0.741±0.036
shoelace	P4	[25]	n/a	n/a	n/a	n/a	n/a
wallet, leather	P4, E2	[28, 33]	114.8	11x9x3	0.930±0.027	1.238±0.059	0.741±0.036
wristwatch, leather band	P4	[28, 30, 33]	21.9	6x2	0.393±0.039	0.324±0.039	0.381±0.037
Grooming							
box of tissues, paper	P5, P1		137.2	23x12x10	0.378±0.027	0.195±0.005	0.316±0.023
hair comb, plastic	P5	[25, 31]	n/a	n/a	n/a	n/a	n/a
hairbrush, wooden	P5	[28]	100.3	22x7x1	0.404±0.046	0.342±0.018	0.317±0.031
lipstick tube, plastic	P5	[31]	21.7	2x7	0.371±0.016	0.253±0.022	0.240±0.030
nail polish bottle, glass	P5		50.3	3x2x8	0.191±0.019	0.121±0.017	0.193±0.010
makeup compact, plastic	P5	[33]	53.3	8x6x19	0.273±0.026	0.149±0.008	0.215±0.015
small mirror	P5	[30]	n/a	n/a	n/a	n/a	n/a
tweezers, anodized metal	P5	[30, 31]	13.3	10x2x1	0.308±0.049	0.410±0.057	0.559±0.028
Ambulation/Transfer							
cane	P6	[28]	n/a	n/a	n/a	n/a	n/a