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ANALYSING FINGER INTERDEPENDENCIES DURING THE PURDUE PEGBOARD TEST AND COMPARATIVE ACTIVITIES OF DAILY LIVING

ABSTRACT

Study Design: Bench, Cross-sectional

Introduction: Information obtained from dexterity tests is an important component of a comprehensive examination of the hand.

Purpose of the Study: To analyse and compare finger interdependencies during the performance of the Purdue Pegboard Test and comparative daily tasks.

Methods: A method based on the optoelectronic kinematic analysis of the precision grip style and on the calculation of cross-correlation coefficients between relevant joint angles, which provided measures of the degree of finger coordination, was conducted on 10 healthy participants performing the Purdue Pegboard Test and two comparative daily living tasks.

Results: Daily tasks showed identifiable interdependencies patterns between the metacarpophalangeal joints of the fingers involved in the grip. Tasks related to activities of daily living resulted in significantly higher cross-correlation coefficients across subjects and across movements during the formation and manipulation phases of the tasks (0.7-0.9), while the release stage produced significantly lower movement correlation values (0.3-0.7). Contrarily, the formation and manipulation stages of the Purdue Pegboard Test showed low finger correlation across most subjects (0.2-0.6), while the release stage resulted in the highest values for all relevant movements (0.65-0.9).

Discussion: Interdependencies patterns were consistent for the activities of daily living, but differ from the patterns observed from the Purdue Pegboard Test.

Conclusions: The Purdue Pegboard Test does not compare well with the whole range of finger movements that account for hand performance during daily tasks.

Keywords: Dexterity, Finger coordination, Hand function, Functional outcome

Level of evidence: N/A

1. INTRODUCTION

1.1 HAND FUNCTION TESTS

Two of the biggest challenges in the health care environment are the effectiveness and time-efficiency of treatment. Both factors can be greatly improved by coupling clinical judgment with appropriate and accurate measurement tools. A robust evaluation of patients with hand impairment conditions must include looking at the patient's performance areas within the context of his or her daily living. In a clinic environment, therapists often evaluate common hand function parameters, such as strength, sensibility, and range of motion, along with the administration of dexterity tests, but may forgo to relate assessment procedures with daily living tasks[1].

Hand assessment methods can also be used for the identification and standardisation of grasping patterns. The identification and assessment of particular hand functional postures are vital to the evaluation of treatment of rehabilitation. Although there is little conformity to specific classifications of grasping patterns, they are consistently characterised as: tripod, precision, lateral precision, power, spherical, and extension grip styles [2–4].

Dexterity tests are often based upon ordinal scales and are still widely used in rehabilitation and therapy[5–8]. The main limitations of these assessments are low reliability and sensitivity and, more importantly, these tests are not robust enough to correlate well with the patient's wide range of hand movement patterns [9].

Although many hand assessment methods have been designed and implemented, there is little or no uniformity among them, leading to a lack of conformity to a standard test of hand function. Traditionally, measurement of hand function has been time-based and subjective to the assessor's opinion, with tests such as the Purdue Pegboard Test, Minnesota Manual Dexterity Test, Functional Dexterity Test, and Southampton Hand Assessment Procedure[6,7,9–11] being widely used for rehabilitation and therapy purposes, however, although time is an easy parameter to measure and manipulate statistically, it is not the most accurate and robust measure of hand function. Furthermore, the role of synergistic movements and interdependencies in the proficient performance of tasks has not been explored and it is not part of most traditional assessments.

Previous works have shown that finger movements during daily tasks rarely involve motion or rotation at a single joint. Anatomical factors, such as interdigit webbings, connections between various tendons, insertions of extrinsic finger muscles, and neuronal connections result in mechanical and neural couplings between various joints. The sum of mechanical and neural coupling generates coordinated movements between various joints [12–15]. Thus the proficient grasping of an object entails simultaneous motion at multiple joints, with correlated rotations [13]. Simultaneous correlated motion at multiple joints has been studied during more dexterous uses of the hand, such as typing [16], playing the piano [17], and haptic interactions [18], but a standard procedure to assess such movement synergies has not been developed. Moreover, previous studies involved sets of tasks and hand postures or force patterns that were not specific enough to be immediately translated into assessment practice [19–21].

The Purdue Pegboard (PBT) is one of the most widely used tests of hand function for therapy, rehabilitation, and treatment assessment purposes. It was developed by Dr. Joseph Tiffin, an Industrial Psychologist at Purdue University, in 1948 [7], and originally intended for assessing the dexterity of assembly line workers.

The PBT tests the quality and the speed of performance of the hand as the person accomplishes a task. More precisely, it assesses proficiency of one particular grasping pattern, the precision grip[16]. It has been shown, however, that there are several factors that account for hand manipulative task performance [5,22–25], and the degree with which the Purdue Pegboard Test assesses individual factors has yet to be investigated.

1.2 KINEMATIC ANALYSIS OF THE HAND

Computerised three-dimensional kinematic analysis is being increasingly used in clinical practice as a standard tool for the evaluation of interventions in patients with motor or postural dysfunction, especially in the case of gait and spinal posture [26–28].

In the case of the hand, different techniques have been used in the past to analyse motor function, such as goniometers, instrumented gloves or motion tracking from digital images[29–31]. Many of these techniques do not allow for the simultaneous measurement of all degrees of freedom and the size of the implemented sensors may interfere with the normal execution of hand activities. The motion tracking of small passive markers (motion capture), however, introduces lower movement restriction, and the three-dimensional instantaneous position of anatomical landmarks allows the calculation of a wider range of degrees of freedom[32–37].

Recent advances in motion capture systems that allow larger capture volumes and higher resolution acquisitions have made possible the measurement of representative activities reducing the patient's inconvenience and the invasiveness of the tests [38–41].

In order to effectively compare kinematic parameters in different patients, the use of cyclical actions in the study of upper limbs movements has been implemented, reducing the complexity represented by non-cyclical tasks[42–44].

The presence of movement synergies and its role in proficient performance of manipulative tasks have been investigated since the 1980s as a simplification of the hands' redundant number of degrees of freedom into a more manageable dimensional space [18].

Muscle activation synergies have been investigated and analysed through Principal Component Analysis and cross-correlation[13,45–47], however, an in-depth cross-correlation analysis of movement synergies during activities of daily living and a traditional dexterity test has yet to be made.

2. PURPOSE OF THE STUDY

The purpose of this study was to quantitatively examine finger interdependencies from joint angle correlations, obtained from motion capture, within and across digits 1–3 (thumb to middle finger) during the performance of the Purdue Pegboard Test and two tasks related to activities of daily living. The study focused on the precision grip style, holding an object on the radial aspect of the distal interphalangeal joint of the middle finger, the pulp of the index finger, and the pulp of the thumb.

The precision grip style allows humans to perform most precision handling tasks, such as writing, buttoning, tying, and picking up small objects, it involves continual adaptation and is a crucial component of normal hand function [2]. There are several factors that account for proficient performance of manipulative daily living tasks[5,25,48–50], and, while the Purdue Pegboard Test has been proved to be a valid and reliable overall precision grip assessment procedure, the degree with which it reflects individual factors accounting for proficient manipulation is still unknown. This study was designed to test whether a relatively small set of movement patterns can be identified from precision grip in a selection of activities of daily living. Moreover, this study aims to identify and analyse the relationship between finger correlation patterns during both the Purdue Pegboard Test and activities of daily living, looking to investigate the degree with which the PBT reflects these patterns as underlying features of manipulative tasks.

3. METHODS

3.1 EXPERIMENTAL PROTOCOL

This study examined 10 healthy participants (6 male, 4 female, all right-handed, age 22-38 years, 26 ± 6.2 years) performing the Purdue Pegboard Test and two tasks related to activities of daily living: picking up a coin and opening a plastic bottle. The activities of daily living were selected as representative of tasks requiring the performance of the precision grip style.

All movements began in a consistent seated posture on a 43 cm high, strait- back chair in front of a 72 cm high table with the torso upright, the right upper arm approximately vertical and forearm horizontal, the fingers in natural full extension (abduction/adduction not specified), and the palm resting on a specified area on the table. Subjects were given written and verbal instructions before being allowed to perform a training trial of each task.

The standardized experimental protocol was developed by testing range of motion, motion capture protocols and subjects' positions.

Participants were evaluated by a single tester, trained to use both standardized procedures and motion capture systems, and all experiments were supervised by an occupational therapist.

Test-retest consistency of the protocol was assessed through a paired t-test with alpha level at 0.05 and with hypothesis testing based on confidence intervals of the test-retest data. The differences did not vary in any systematic way over the range of measurement and all measurements were within the 95% limits of agreement.

The subjects carried out three repetitions of each task with a 10-second pause between each trial.

In the first task, subjects performed the Purdue Pegboard Test, reaching forward over a distance of approximately 35 cm to grasp a metal peg (2 mm in diameter), placing it into a hole on the Purdue Pegboard, and returning the hand to the initial posture.

In the second task, subjects maintained the same initial posture as in the first task and reached forward over a distance of approximately 35 cm to grasp a British one-pound coin (22.5 mm in diameter, 3.15 mm in thickness), placed it on a specified mark on the table, and returned the hand to the initial posture.

For the third task the subjects reached forward from the starting position, gasped a 500 ml plastic bottle and unscrew the lid with the dominant hand, using a precision grip style. The plastic lid was then placed on a specific area on the table (Figure 1).

The University of Sheffield's Department of Mechanical Engineering Ethics Committee approved the experimental protocol.

3.2 DATA ACQUISITION

The acquisition technique consisted of the placement of 25 reflective markers (diameter 4mm) on different anatomical hand landmarks.

From the index to little fingers, five markers were placed as follows: first marker on the metacarpophalangeal base, second marker on the knuckle, third on the proximal interphalangeal (PIP) joint, fourth on the distal interphalangeal (DIP) joint and, finally, the fifth marker on the nail (Figure 2).

For the thumb, first marker was placed on the metacarpophalangeal base, second marker on the MCP joint, fourth on the IP joint and the fifth marker on the nail. One marker was placed on the wrist, aligned with the middle finger, on the wrist dorsum (Figure 2).

A ten-camera Vicon T-160 motion capture system (Oxford Metrics Ltd., UK) recorded the reflective marker movements at a sampling frequency of 120 Hz, and then output the time-varying marker coordinates in a three-dimensional laboratory coordinate system (X–Y–Z) established through calibration. The data was then processed through a second order Butterworth low-pass filter with a cut-off frequency of 5 Hz.

A local coordinate system X_0–Y_0–Z_0 was established to facilitate kinematic descriptions and definitions (Figure 2). The origin of this local coordinate system was the marker adhered to the dorsal landmark of wrist. The coordinates of the markers measured in the global (laboratory) coordinate system (X –Y –Z) were transformed and expressed in the local coordinate system (X_0–Y_0–Z_0). From the local coordinates, the time-varying angles for all the involved flexion–extension and thumb abduction-adduction joints were derived through a computational procedure.

3.3 DATA ANALYSIS

The analysis consisted of the computation of the cross-correlation coefficient matrix for all joint angles of interest. A matrix X, whose rows are observations (instantaneous joint angles) and whose columns are variables (degree of freedom), was defined from data from the last trial of each task for each subject in order to reduce error due to learning effect and provide stability to the data.

The matrix R of correlation coefficients was calculated from the matrix X. The matrix R is related to the covariance matrix C by:

$$R(i,j) = \frac{C(i,j)}{\sqrt{\left(C(i,i)C(j,j)\right)}}$$

Where R, is the zeroth lag of the normalized covariance function.

Significance of the correlation values was examined for $p < 0.5$, and for all correlation coefficients $n = 10$, $df = 8$.

The matrix R was calculated for each trial every 20 frames (0.2 second**),** increasing the precision of the analysis and allowing for the splitting of the tasks into 3 stages: formation of the grip style, manipulation, and release, each one of them with an average of 3 20-frame sections.

The formation stage was defined as the portion of the task between the start of the movement and the first contact with the object. The manipulation stage was defined as the period of the task between the first contact of the dominant hand with the object and the moment no contact between the hand and the object is detected. Finally, the release stage starts when the hand stops making contact with the object and ends with the hand in the starting posture (Figure 3).

Particular attention was placed on the correlation coefficients of the MCP flexion of the thumb, index, and middle fingers as well as thumb abduction, as these fingers have an active role in the precision grip style.

4. RESULTS

4.1 PURDUE PEGBOARD TEST

Formation stage: In the Purdue Pegboard Test experiment the metacarpophalangeal joints of the index and middle fingers showed high correlation coefficients between them (0.8 - 0.95) during the formation stage of the task. The metacarpophalangeal of the thumb, however, had low correlation coefficients with respect to the metacarpophalangeal of index and middle fingers (0.1 – 0.5). Correlation coefficients between all the joints analysed fell during the final segment of the formation stage, when the hand approached the object and prepared to make contact with the board, this was particularly noticeable in the correlation coefficients between the metacarpophalangeal joint of the thumb and the same joint of the index and middle fingers (Table 1).

Manipulation stage: During the manipulation stage, the metacarpophalangeal joint of the thumb had low correlation values with respect to the metacarpophalangeal joints of both the index and middle fingers (0.2 - 0.5). The metacarpophalangeal joints of index and middle fingers showed higher correlation values between them during the first part of the manipulation stage. The last part of the manipulation stage, which includes the insertion of the peg into the hole, produced low correlation values for all the joints under analysis (0.3 - 0.5) (Table 1, 2).

Release stage: During the release stage of the test correlation values between the metacarpophalangeal joints of index and middle fingers raised to levels above 0.8 for most subjects, while correlation coefficients from movements involving the thumb increased when compared with previous stages, showing a smooth and coordinated extension of this fingers during the dissolution of the grasping pattern (Table 1).

4.2COIN PICK UP

Formation stage: During the coin experiment, the metacarpophalangeal joints of the thumb, index and middle fingers had high correlation values between them for the first half of the formation stage (0.8 - 0.95). The metacarpophalangeal joint of the thumb showed lower correlation values with respect to index and middle MCP joints for the last part of the formation stage (0.2 - 0.4) for 90% of the subjects (Table 3, 4).

Manipulation stage: The manipulation stage of the coin task showed high correlation values between the metacarpophalangeal joints of the thumb, index and middle fingers (0.8 -0.95), indicating a smooth and coordinated grasp and manipulation of the coin across all subjects (Table 4).

Release stage: In the release stage of the task, the metacarpophalangeal joint of the thumb had the lowest correlation coefficients with respect to the index and middle fingers' metacarpophalangeal joint, fluctuating between 0.2 and 0.9. Additionally, the correlation coefficients between index and middle fingers decreased with respect to previous stages of the task, indicating the dissolution of the grasping pattern presented low coordination between the fingers involved, particularly between the thumb and the index and middle fingers (Table 4).

4.3 BOTTLE OPENING

Formation stage: In the bottle experiment, the metacarpophalangeal joints of the index, middle and thumb had high correlation coefficients between them throughout the formation stage of the task (0.8 - 0.95) (Table 5).

Manipulation stage: Throughout the manipulation stage, the metacarpophalangeal joints of index and middle fingers presented high correlation values (0.8 - 0.95). The metacarpophalangeal joint of the thumb, however, presented moderate to low correlation values with respect to the index and middle fingers (0.5 - 0.7) for most subjects (Table 5).

Release Stage: The release stage resulted in low correlation coefficients between the metacarpophalangeal joints of the thumb and the index and middle fingers', indicating the dissolution of the grip style was completed with a low degree of interdependencies between the fingers involved in the activity, this behaviour could be generally observed from 80% of the subjects (Table 5).

5. DISCUSSION

Previous studies have employed various data acquisition techniques and analysis methods to examine finger movement coordination. However, there are just a few comprehensive quantitative descriptions of the movement patterns from a kinematic perspective under multi-finger, multi-joint tasks [20,47,15]. The current study was an attempt to contribute to these studies by utilising the latest measurement technology to obtain kinematic data and investigate the robustness of a traditional dexterity test, the Purdue Pegboard Test, by comparing finger movement correlation patterns during the performance of the test with those measured during tasks related to activities of daily living.

Although the complex correlated movements of the hand have been investigated in previous studies, most paradigms have included a wide set of tasks and grasping patterns, and were not specific enough to be compared with individual grip styles and existing assessment methods [20,21,51,52]. Moreover, although synergistic movement has been studied during sophisticated uses of the hand, investigations into how movement patterns are assessed by traditional dexterity tests and how it translates into daily living tasks were still lacking.

This study presents evidence of identifiable finger correlation patterns during daily living tasks and, particularly, it shows that activities of daily living requiring a precision grip style have identifiable movement patterns between the metacarpophalangeal joints of the fingers involved in the activity. Moreover, the current study discovered that such movement patterns are consistent for the selected activities of daily living, but differ from the patterns observed from the Purdue Pegboard Test.

Furthermore, it has been shown that the Purdue Pegboard Test does not accurately assess the true correlated movement occurring during precision grip.

The tasks selected for this study require the performance of the precision grip style and were sub-divided into approach, formation of the grip style, manipulation, and release stages.

During the formation stage of activities of daily living correlation coefficients between the metacarpophalangeal joints of the thumb, index and middle fingers were consistently high across most subjects, indicating interdependent movement due to the fine controlled nature of the task, requiring manipulation of small objects in a reduced space between the thumb, index and middle fingers. During the same stage from the Purdue Pegboard Test, the correlation coefficients were lower between the thumb and the index and middle fingers when compared to those from activities of daily living across participants, indicating the formation of the grasping pattern during completion of the test involved considerably lower levels of finger coordination, with participants distinctly struggling to co-ordinately perform the required grasping movement.

Differences during the manipulation stage of the tasks were more significant, as high correlation coefficients were observed from the activities of daily living throughout this stage across all subjects, with higher levels of coordination between the active fingers, while the correlation values from the Purdue Pegboard Test during this stage were mostly low, particularly between the metacarpophalangeal of the thumb and the middle and index fingers (Table 1 and 2). The coin and bottle tasks involved high levels of interdependencies as seen by the resulting correlation coefficients between the relevant joint angles (Tables 3-5), while participants struggled more with the pegs of the test, producing lower levels of interdependence and a less coordinated movement across the fingers under analysis. Maintaining the fingers’ posture to transport the peg resulted in the lowest correlation coefficients during the manipulation stage, indicating participants struggled to maintain the grip style.

In addition, the release stage of the Purdue Pegboard Test produced the highest correlation coefficients for the joints under analysis, while for the activities of daily living it was during this stage that the lowest correlation values were observed (Tables 1-5).

Generally, finger interdependencies patterns observed from participants performing the Purdue Pegboard Test differ greatly from patterns observed during performance of tasks related to activities of daily living. Subjects proficiency to perform coordinated movements with the fingers to complete activities of daily living was, generally, greater than that to perform the Purdue Pegboard Test, this could be due to the nature of the test as an assessment tool and the lack of familiarity with such procedures compared to daily living tasks.

The use of motion capture technology to collect movement data proved to be flexible, accurate and time-efficient. The system used for the data acquisition was capable of recording 16 megapixel video with a precision of 0.5mm of translation and 0.5 degrees of rotation, along with capture speeds of 160 fps, thus, making possible the collection of a wide range of quick, precise movements. Furthermore, motion capture systems allow for data collection in a wide variety of conditions and lab environments, giving patients and researchers the flexibility of naturalistic environments and setups. Although the cost of the software, equipment and personnel required for most motion capture systems can still be potentially prohibitive for a generalised clinical practice, recent technological developments are increasing the affordability of this type of technology, particularly when comparing cost-effectiveness against traditionally used methods and techniques.

CONCLUSIONS

In conclusion, although finger manipulative tasks can be carried out in seemingly an infinite number of ways, standard motion patterns can be identified and assessed by analysing finger joint movement correlation. Direct measurement and in-depth analysis allowed the identification of some of these movement patterns and showed some of the limitations of the Purdue Pegboard Test when used as a measure of the patient's ability to perform daily tasks.

A comparative look at the connection between the same stage of two tasks and the differences between particular stages of dexterity tests and daily tasks led to new insights and rendered evidence of the limitations of traditional hand function assessment methods.

Results from this study suggest that there are significant differences in finger movement patters when comparing sets of precision manipulative tasks. Such differences were particularly evident when splitting the tasks into three phases: formation, manipulation, and release. Tasks related to activities of daily living resulted in significantly higher correlation coefficients across subjects and across movements during the first two stages of the tasks (0.7-0.9), while the release stage produced significantly lower movement correlation values (0.3-0.7). Contrarily, the formation and manipulation stages of the Purdue Pegboard Test showed low finger correlation across most subjects (0.2-0.6), while the release stage resulted in the highest values for all relevant movements (0.65-0.9).

Furthermore, the study provided additional evidence to support the conjecture that traditional hand function assessment methods based on time cannot cover the wide range of factors that account for hand performance during activities of daily living. Particularly, finger movement correlations during performance of the Purdue Pegboard Test were shown to translate poorly into movement correlations during daily tasks that require a precision grip style.

Future work must be focused on increasing the method's degree of standardization in order to obtain repeatable and reliable results across patients. The evaluation of a variety of functional tests and their relation to finger movement correlations across a range of frequently used grasping patterns must also be explored in future studies. In general, further development of objective and reliable evaluation methods for upper extremity tasks is required, particularly for standard and goal-oriented tasks.

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REFERENCES

1. Arthritis Research UK. *Osteoarthritis in General Practice.*; 2013.
2. Landsmeer JMF. Power Grip and Precision Handling. *Ann Rheum Dis*. 1962;21(2):164-170. doi:10.1136/ard.21.2.164.
3. Taylor C, Schwartz R. The Anatomy and Mechanics of the Human Hand. *Artif Limbs*. 1955;2(2):22-35.
4. Napier JR. The Prehensile movements of the human hand. *J bone Jt Surg*. 1956.
5. Fleishman E a., Hempel WE. A Factor Analysis of Dexterity Tests. *Pers Psychol*. 1954;7(1):15-32. doi:10.1111/j.1744-6570.1954.tb02254.x.
6. Surrey LR, Nelson K, Delelio C, et al. A comparison of performance outcomes between the Minnesota Rate of Manipulation Test and the Minnesota Manual Dexterity Test. *Work*. 2003;20(2):97-102.
7. Tiffin J, Asher E. The Purdue pegboard test; norms and studies of reliability and validity. *J Appl Psychol*. 1948;32(3):234-47.
8. Peterson LR, Centre R. The Moberg Pickup Test: *J Hand Ther*. 1999;(December):309-312.
9. Light CM, Chappell PH, Kyberd PJ. Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity. *Arch Phys Med Rehabil*. 2002;83(6):776-783. doi:10.1053/apmr.2002.32737.
10. Mathiowetz V, Volland G, Kashman N, Weber K. Adult Norms for the Box and Block Test of Manual Dexterity. *Am J Occup Ther*. 1985;39(6).
11. Aaron DH, Jansen CWS. Development of the Functional Dexterity Test (FDT): construction, validity, reliability, and normative data. *J Hand Ther*. 1992;16(1):12-21.
12. Su F-C, Chou YL, Yang CS, Lin GT, An KN. Movement of finger joints induced by synergistic wrist motion. *Clin Biomech (Bristol, Avon)*. 2005;20(5):491-7. doi:10.1016/j.clinbiomech.2005.01.002.
13. Santello M, Soechting JF. Force synergies for multifingered grasping. *Exp Brain Res*. 2000;133(4):457-467. doi:10.1007/s002210000420.
14. Grinyagin I V, Biryukova E V, Maier M a. Kinematic and dynamic synergies of human precision-grip movements. *J Neurophysiol*. 2005;94(4):2284-94. doi:10.1152/jn.01310.2004.
15. Tagliabue M, Ciancio AL, Brochier T, Eskiizmirliler S, Maier M a. Differences between kinematic synergies and muscle synergies during two-digit grasping. *Front Hum Neurosci*. 2015;9(March):1-17. doi:10.3389/fnhum.2015.00165.
16. Soechting JF, Flanders M. Flexibility and repeatability of finger movements during typing: Analysis of multiple degrees of freedom. *J Comput Neurosci*. 1997;4(1):29-46. doi:10.1023/A:1008812426305.
17. Engel KC, Flanders M, Soechting JF. Anticipatory and sequential motor control in piano playing. *Exp brain Res*. 1997;113(2):189-199.
18. Thakur PH, Bastian AJ, Hsiao S. Multidigit movement synergies of the human hand in an unconstrained haptic exploration task. *J Neurosci*. 2008;28(6):1271 - 1281.
19. Todorov E, Jordan MI. Smoothness maximization along a predefined path accurately predicts the speed profiles of complex arm movements. *J Neurophysiol*. 1998;80:696-714.
20. Thakur PH, Bastian AJ, Hsiao SS. Multidigit movement synergies of the human hand in an unconstrained haptic exploration task. *J Neurosci*. 2008;28(6):1271-1281. doi:10.1523/JNEUROSCI.4512-07.2008.
21. Castellini C, Van Der Smagt P. Evidence of muscle synergies during human grasping. *Biol Cybern*. 2013;107(2):233-245. doi:10.1007/s00422-013-0548-4.
22. Pennathur A, Contreras LR, Arcaute K, Dowling W. Manual dexterity of older Mexican

American adults: a cross-sectional pilot experimental investigation. *Int J Ind Ergon*. 2003;32(6):419-431. doi:10.1016/j.ergon.2003.07.001.

23. Vanbellingen T, Kersten B, Bellion M, et al. Impaired finger dexterity in Parkinson's disease is associated with praxis function. *Brain Cogn*. 2011;77(1):48-52. doi:10.1016/j.bandc.2011.06.003.
24. Valero-Cuevas FJ, Smaby N, Venkadesan M, Peterson M, Wright T. The strength-dexterity test as a measure of dynamic pinch performance. *J Biomech*. 2003;36(2):265-70.
25. Latash ML, Turvey MT. *Dexterity and Its Development,* . Mahwah, New Jersey: Lawrence Erlbaum Associates, Inc; 1996.
26. Cappozzo A, Della Croce U, Leardini A, Chiari L. Human movement analysis using stereophotogrammetry. Part 1: theoretical background. *Gait Posture*. 2005;21(2):186-96. doi:10.1016/j.gaitpost.2004.01.010.
27. Cappozzo A, Catani F, Croce U Della, Leardini A. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin Biomech (Bristol, Avon)*. 1995;10(4):171-178.
28. Barbiˇ J, Safonova A, Hodgins JK, Faloutsos C, Pollard NS. Segmenting Motion Capture Data into Distinct Behaviors. 2004:185-194.
29. Dipietro L, Sabatini AM, Member S, Dario P. A Survey of Glove-Based Systems and Their Applications. *IEEE Trans Syst man Cybern*. 2008;38(4):461-482.
30. Winges S a, Weber DJ, Santello M. The role of vision on hand preshaping during reach to grasp. *Exp brain Res*. 2003;152(4):489-98. doi:10.1007/s00221-003-1571-9.
31. Ellis B, Bruton A. A study to compare the reliability of composite finger flexion with goniometry for measurement of range of motion in the hand. *Clin Rehabil*. 2002;16(5):562-570. doi:10.1191/0269215502cr513oa.
32. Chiari L, Della Croce U, Leardini A, Cappozzo A. Human movement analysis using stereophotogrammetry. Part 2: instrumental errors. *Gait Posture*. 2005;21(2):197-211. doi:10.1016/j.gaitpost.2004.04.004.
33. Moeslund TB, Granum E. A Survey of Computer Vision-Based Human Motion Capture. *Comput Vis Image Underst*. 2001;81(3):231-268. doi:10.1006/cviu.2000.0897.
34. Rash GS, Belliappa PP, Wachowiak MP, Somia NN, Gupta a. A demonstration of validity of 3-D video motion analysis method for measuring finger flexion and extension. *J Biomech*. 1999;32(12):1337-41.
35. Bodenheimer B, Rose C, Rosenthal S. The Process of Motion Capture : Dealing with the Data 1 Introduction 2 Basic Motion Capture Process. :1-14.
36. Degeorges R, Parasie J, Mitton D, Imbert N, Goubier J-N, Lavaste F. Three-dimensional rotations of human three-joint fingers: an optoelectronic measurement. Preliminary results. *Surg Radiol Anat*. 2005;27(1):43-50. doi:10.1007/s00276-004-0277-4.
37. Small CF, Bryant JT, Pichora DR. Rationalization of kinematic descriptors for three-dimensional hand and finger motion. *J Biomed Eng*. 1992;14(2):133-41.
38. Carpinella I, Mazzoleni P, Rabuffetti M, Thorsen R, Ferrarin M. Experimental protocol for the kinematic analysis of the hand: definition and repeatability. *Gait Posture*. 2006;23(4):445-54. doi:10.1016/j.gaitpost.2005.05.001.
39. Warlow OM, Lawson SE. A technique for motion capture of the finger using functional joint centres and the effect of calibration range of motion on its accuracy. In: *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*.Vol 226.; 2012:360-367. doi:10.1177/0954411912442133.
40. Braido P, Zhang X. Quantitative analysis of finger motion coordination in hand manipulative and gestic acts. *Hum Mov Sci*. 2004;22(6):661-78.

doi:10.1016/j.humov.2003.10.001.

41. Sancho-Bru JL, Jarque-Bou NJ, Vergara M, Pérez-González A. Validity of a simple videogrammetric method to measure the movement of all hand segments for clinical purposes. *Proc Inst Mech Eng H*. 2014;228(2):182-9. doi:10.1177/0954411914522023.
42. Murgia A, Kyberd PJ, Chappell PH, Light CM. Marker placement to describe the wrist movements during activities of daily living in cyclical tasks. *Clin Biomech (Bristol, Avon)*. 2004;19(3):248-54. doi:10.1016/j.clinbiomech.2003.11.012.
43. Gentilucci M, Caselli L, Secchi C. Finger control in the tripod grasp. *Exp brain Res*. 2003;149(3):351-60. doi:10.1007/s00221-002-1359-3.
44. Gioioso G, Salvietti G, Malvezzi M, Prattichizzo D. Mapping Synergies From Human to Robotic Hands With Dissimilar Kinematics: An Approach in the Object Domain. *IEEE Trans Robot*. 2013;29(4):825-837. doi:10.1109/TRO.2013.2252251.
45. Maier MA, Hepp-Reymond MC. EMG activation patterns during force production in precision grip. II. Muscular synergies in the spatial and temporal domain. *Exp brain Res*. 1995;103(1):123-36.
46. Soechting JF, Lacquaniti F. An assessment of the existence of muscle synergies during load perturbations and intentional movements of the human arm. *Exp brain Res*. 1989;74:535-548.
47. Gabiccini M, Bicchi a., Prattichizzo D, Malvezzi M. On the role of hand synergies in the optimal choice of grasping forces. *Auton Robots*. 2011;31:235-252. doi:10.1007/s10514-011-9244-1.
48. Tenneti R, Johnson D, Goldenberg L, Parker R a., Huppert F a. Towards a capabilities database to inform inclusive design: Experimental investigation of effective survey-based predictors of human-product interaction. *Appl Ergon*. 2012;43(4):713-726. doi:10.1016/j.apergo.2011.11.005.
49. Reilly KT, Hammond GR. Human handedness: is there a difference in the independence of the digits on the preferred and non-preferred hands? *Exp brain Res*. 2004;156(2):255-62. doi:10.1007/s00221-003-1783-z.
50. Wittenborn JR. Mechanical Ability, its nature and measurement. II. Manual Dexterity. *Educ Pyscol Measmt*. 1945;5:395-409.
51. Latash ML, Scholz JF, Danion F, Schöner G. Finger coordination during discrete and oscillatory force production tasks. *Exp brain Res*. 2002;146(4):419-32. doi:10.1007/s00221-002-1196-4.
52. Berger DJ, d’Avella A. Effective force control by muscle synergies. *Front Comput Neurosci*. 2014;8(April):46. doi:10.3389/fncom.2014.00046.