Humanoid Hand

Finalized Testing Plan

Noah Enlow, Project Manager

Tyler LeBeau, Logistics Manager

Joseph Maresh, CAD Engineer

David Lutz, Manufacturing Engineer

Justin Alonzo, Finacial Manager

Markus Steinebrunner, Test Engineer

Spring 2025-Fall 2025

Project Sponsors: Dr. Zach Lerner, Dr. Reza Razavian

Subject Matter Experts: Daniel Colley, Landon Coonrod

Instructor: Carson Pete

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

The goal of this project is to design a highly dexterous robotic hand which will serve as a testbed for two of NAU's research labs to dip their toes into the field of prosthetics. The sponsors of this project are Dr. Zach Lerner and Dr. Reza Razavian. The sponsors have set forth two major goals for the hand: 1) to be able to play a tune on the piano and 2) to be able to catch a ball. These requirements set forth a high bar for speed, strength, and dexterity.

The major project deliverables are the team's 100% Hardware Check November 3rd, our Final CAD, Poster, and PowerPoint on November 17th, the Final Report on December 1st, and the EFEST Expo on December 5th. The first prototype will be a 3D printed finger design, displaying functional tendon actuation and angle sensing in the joints. The second prototype will be a 3D printed thumb design, also displaying tendon actuation and angle sensing. The success metrics for the final design, and toward which these prototypes will be aiming are as follows. The fingers will need to be capable of exerting 1 N of force at the tip of the finger and will need to have the full or near-full range of motion of the biological hand in order to be able to play the piano. Moreover, the motors will need to be capable of between 100-300 RPM in order to meet the catching requirement.

The overall design of the hand is still largely undetermined. The work of the team so far has been directed toward establishing a solid finger design and thinking about what actuation style will be used and how. At this point, the established design consists of what follows.

Fingers will be primarily tendon driven with servos at the base of the fingers to facilitate splaying the fingers. The thumb will likely be similar, using tendons to flex and extend the thumb and two servos enabling the thumb's more complex motion. The fingers will have four tendon attachment points. One on the top side of the first and second segment of the finger each, and similarly for the bottom (palmar side) of the finger. The third segment of the finger will be mechanically linked to the motion of the second joint to cut down on how many motors are needed. There will likely be fourteen motors. Eight of them will reside in the forearm, driving the tendons. The other six will be in the hand, controlling the splaying of the fingers and the motion of the base joint of the thumb. The motors in the forearm will be BLDC motors, chosen for their speed and torque. The motors in the hand will be servos, chosen for their smaller size. Lastly, each finger will house 3 angle sensors. One at the base joint, one at the second joint of the finger, and one at the finger tip. The angle sensors will be there to ensure accuracy and repeatability of motion. Because the last segment of the finger will be mechanically linked to the second segment of the finger, its angular position can be inferred, avoiding the need for a third angle sensor in the finger.

The results from our literature review and mathematical modelling indicate that motors will need to be wisely chosen, joints will need to be well-made, and the control scheme will need to be well-programmed. The hand is a complex machine and it is no simple task to adequately mimic its capabilities. The mathematical modelling section of this document goes into more detail regarding these requirements.

TABLE OF CONTENTS

Contents

1 Design Requirements Summary

The following summarizes the customer and engineering requirements that guide the design, testing, and validation of the humanoid hand. These requirements were based on sponsor expectations.

1.1 Customer Requirements

Table 1: Customer Requirements

Customer Requirement	Description
CR1	Strong enough to play the piano and catch a ball
CR2	Fast enough to play the piano and catch a ball
CR3	Accurate dimensions
CR4	Accurate weight
CR5	Within budget
CR6	Many degrees of freedom
CR7	Uses standard form of power to function
CR8	Does not overheat
CR9	Has basic and functional UI
CR10	Reliable
CR11	Precision of motion

1.2 Engineering Requirements

Table 2: Engineering Requirements

Engineering Requirement	Description
ER1	Grip force of 45-50N
ER2	Time from full extension to full closure 200-250ms
ER3	Within 1-1.5 scale of average person's hand and forearm
ER4	Approximately 3-4kg
ER5	Cost of manufacturing <$1500
ER6	15 degrees of freedom
ER7	Operates with 1-3 120V plugs
ER8	At high operating load, no component exceeds 75°C
ER9	Can be operated by Lerner or Reza with a <10 min demo
ER10	Each joint operable near 10k motions
ER11	Able to predict finger placement within +/- 5mm based on sensor data

2 Top Level Testing Summary

The tests outlined below will verify each and every customer and engineering requirement. This table helps ensure that all are verified.

Table 3: Top Level Testing Summary

Experiment/Test	Relevant Design Requirements
T1- Static Grip Strength	CR1, ER1
T2- Actuation Speed Test	CR2, ER2
T3- Weight and Size Test	CR3, CR4, ER3, ER4
T4- Durability and Thermal Release	CR8, CR10, ER8, ER10
T5- Sensor Accuracy Calibration	CR11, ER11
T6- Power Draw Test	CR7, ER7
T7- User Interface Evaluation	CR9, ER9
T8- Functional Performance Test	CR1, CR2, CR11, ER1, ER2, E11
T9- Degrees of Freedom and Budget Evaluation	CR5, CR6, ER5, ER6

3 Detailed Testing Plan

3.1 Test 1 – Static Strength

Test Summary:

These tests will verify that the humanoid hand meets the required grip force (45-50N) and will test the static force exerted by a single finger. The test evaluates the whole hand grip force and maximum static force. This will be composed of two tests; one will use a hanging scale to measure static strength, and the other will use a load cell to measure the maximum extended finger force.

Equipment: Load cell, hanging scale, rigid mounting fixture, data logger

Variables Measured: Applied fingertip force (N) and grip force (N)

Variables Calculated: Convert mass to force; mean and standard deviation of grip forces

Procedure (Static Finger):

1. Mount the hand securely to a rigid base to prevent movement during testing
2. Zero load cell
3. Place the cell under the fingertip and command the finger to close. Record peak normal force
4. Repeat 10 times per finger
5. Inspect your hand for slippage or permanent deformation after testing.

Procedure (Hanging Scale):

1. Mount the hand securely to a rigid base to prevent movement during testing
2. Place bar connected to the scale in the hand and command full close
3. Pull steadily on scale and record heaviest weight held for 10 seconds without slippage
4. Repeat with progressively heavier objects until first signs of failure

Results:

The expected fingertip force is approximately 3-5N, and the average whole-hand grip force should fall within 45-50N. A successful test will demonstrate repeatable forces within 20% standard deviation and no evidence of material or mechanical failure.

Conclusion:

If measured forces meet the required range and components remain undamaged, the grip system satisfies ER1 and CR1. Consistency across trials will confirm mechanical reliability and actuation strength.

3.2 Test 2 – Actuation Speed

Test Summary:

This test measures the time required for a full open to close motion cycle. Two position sensors, one at full extension and one at full close, will be used to determine actuation time. This validates ER2 and CR2, ensuring the system achieves the 200-250ms actuation goal required for responsive control and dynamic hand motions.

Equipment: FSRs (Lerner's Lab), microcontroller with timestamp logging, stopwatch

Variables Measured: time between extension and closure (ms)

Variables Calculated: Average actuation time and standard deviation

Procedure:

1. Mount one sensor at full extension and another at full closure
2. Connect sensors to microcontroller
3. Command finger to perform 10 cycles of full open and close
4. Record time between sensor activation
5. Repeat 3 sets of 10 cycles to confirm repeatability

Results:

Expected actuation time is 200-250 ms. Any time lower than 250 ms is an acceptable result.

Conclusion:

If the measured average actuation time is within 200-250 ms and consistent across trials, ER2 and CR2 are satisfied, confirming adequate motor speed and control responsiveness.

3.3 Test 3 – Weight and Size

Test Summary:

This test verifies that the assembled hand fits the weight and geometric design targets of ER3 and ER4 as well as CR3 and CR4.

Equipment: Digital scale, calipers, Solidworks model, tape measure

Variables Measured: Hand weight (kg), dimensions (cm)

Variables Calculated: Percent difference between average anatomical values and robotic hand values

Procedure:

1. Weight the assembled hand using a digital scale (record 3 trials)
2. Measure hand length, finger length, palm width, forearm diameter (at wrist and base) and forearm height with calipers and measuring tape
3. Compare against human averages
4. Document deviations and verify scale ratios

Results:

The expected weight is 3-4kg and measurements should be roughly 1-1.5x human dimensions. Average adult male measurements listed in Procedure step 2) are 19.4 [1], 7.8 [2], 9.0 [1], 54 [3], 90 [4], 29 [1] cm respectively.

Conclusion:

If weight and size remail within tolerance, the design meets ER3, ER4, CR3 and CR4 ensuring human-scale geometry and mass.

3.4 Test 4 – Durability and Thermal Release

Test Summary:

This test determines a finger's operational lifespan under cyclical loading confirming ER8, CR8, ER10 and CR 10.

Equipment: Motorized finger in rig, motor controller with cycle counter, time lapse video, laser thermometer

Variables Measured: Cycle count to failure, temperature (C)

Variables Calculated: Failure rate and performance degradation

Procedure:

1. Mounted finger to cycling rig and set actuation to 1 Hz
2. Run continuous open-close cycles recording count and taking timelapse video
3. Pause every 1000 to inspect for damage
    a. Measure and record motor, driver board, and power supply temperatures

4. Continue to failure or 15k cycles

Results:

The target is a 10,000-cycle minimum and ideally it will survive more than 15,000. At 1 Hz this is 4 hours and 10 minutes of continuous run time. The temperature should not exceed 75°C

Conclusion:

If the finger exceeds 10,000 cycles with no tendon issues or significant degradation, ERs8 10, and CRs 8 and 10 is met. This validates material durability and assembly reliability.

3.5 Test 5 – Sensor Accuracy Calibration

Test Summary:

This test validates positional accuracy of the sensors to ensure ER11 and CR11.

Equipment: Camera and calibration grid,

Variables Measured: Actual finger joint angles(degrees)

Variables Calculated: Positional error and repeatability

Procedure:

1. Command fingertips to target position and take a picture of finger in final position
2. Using the photograph measure actual angles of each joint
3. Calculate the deviation between commanded and measured points
4. Repeat each target 5 times and record mean and standard deviation

Results:

Expected mean error should be 3-5mm with a standard deviation of ~1mm.

Conclusion:

If the fingertip deviation is within 5mm and repeatable, ER11 and CR11 are satisfied. This confirms the precision of motion tracking and sensor calibration.

3.6 Test 6 – Power Draw

Test Summary:

This test measures the electrical power consumption to verify ER7 (standard 120 V operation) and CR 7 (safe and efficient power use)

Equipment: Power analyzer, timer, data logger, laser thermometer

Variables Measured: Power (W)

Variables Calculated: Average power and efficiency

Procedure:

1. Connect hand's power input to power analyzer
2. Record wattage at 1 min intervals during 2 scenarios
    a. Low Load: Finger calibration and idle movements (0.3Hz)
    b. High Load: Stress ball and command close all the way-1 min
3. Plot power vs time and temp vs time

Results:

At a nominal voltage of 120 V and an estimated current of 2-5A, the expected wattage is 360W.

Conclusion:

If total power is less than 500W a ER7 and CR7 are met, confirming safe electrical operations.

3.7 Test 7 – User Interface

Test Summary:

This test evaluates user feedback and client satisfaction confirming ER9 and CR9.

Equipment: User feedback form

Variables Measured: User satisfaction scoring

Variables Calculated: N/a

Procedure:

1. Create qualitative feedback form
2. Have Lerner and Reza answer qualitative feedback form
3. Calculate average scoring

Results:

The expected results are an average of 4/5 scoring on the qualitative feedback form.

Conclusion:

If the clients are able complete the tasks quickly and give 4/5 average scores for the qualitative feedback, ER9 and CR+ will be satisfied, thus validating client satisfaction.

3.8 Test 8 – Functional Performance

Test Summary:

This test evaluates real world performance: playing piano keys in rhythm and holding various objects verifying ER1, ER2, and ER11 as well as the corresponding CRs.

Equipment: Load Cell, metronome, object set, (ping-pong ball, tennis ball, cup, rubics cube, plate, paper, and pencil), timer, force gauge

Variables Measured: Timing error (ms), tip force (N), hold duration (s)

Variables Calculated: mean timing deviation, retention rate, average tip force

Procedure:

1. For piano test
    a. Program finger to press load cell at 1/16th notes at 120 BPM
    b. Record 10 trials and time stamps for presses
    c. Record measured tip force for each press
2. For object holding:
    a. Grasp each test object for 30s
    b. Apply small perturbations to simulate movement
    c. Record whether object is retained or slips

Results:

At 120 BPM a 1/16th note is .125 seconds. Key presses should be within 25 ms of desired time. The tip force must be greater than 1N per keypress. The objects held must remain secure for 30s

Conclusion:

If the mean timing error is less than 25ms and all objects are retained, the system meets ER1, ER2, and ER9, confirming functional dexterity, timing and grasp reliability.

3.9 *Test 9* – Degrees of Freedom and Budget Evaluation

Test Summary:

This test evaluates the hands degrees of freedom (DOF) as well as manufacturing cost. This will validate ER 5 and 6 as well as the corresponding CRs.

Equipment: Material List for Final Product, Final hand

Variables Measured: Number of DOF, cost of final product

Variables Calculated: N/a

Procedure:

1. Count the number of DOF in the hand
2. Sum the value of each part in the final hand

Results:

The hand should have at least 15 DOF and the final cost should be below $1500

Conclusion:

If the hand has 15 DOF and the cost is below $1500 then it will pass ER 6, ER7, CR6, and CR7.

4 Specification Sheet Preparation

Below are tables prepared to receive and represent our testing results. They lay out the pass criteria, tolerances, and whether or not the client accepted the results in one concise area.

Table 4: Customer Requirement Specification Sheet Preparation

Customer Requirement	CR met? (yes or no)	Client Acceptable (yes or no)
CR1- Strong enough to play and catch a ball		
CR2- Fast enough to play piano and catch a ball		
CR3- Accurate dimensions		
CR4- Accurate weight		
CR5- Within budget		
CR6- Many degrees of freedom		
CR7- Uses standard form of power		
CR8- Does not overheat		
CR9- Has a basic and functional UI		
CR10- Reliable		
CR11- Precision of motion		

Table 5: Engineering Requirement Specification Sheet Preparation

Engineering Requirement	Target	Tolerance	Measured/ Calculated Value	ER met? (yes or no)	Client Acceptable (yes or no)
ER1- Grip force	45-50N	5N			
ER2- Full extension to full closure	200-250ms	25ms			
ER3- Scale of human dimensions	1-1.5x	N/a			
ER4- Accurate weight	3-4kg	.3kg			
ER5- Within budget	<$1500	N/a			
ER6- Degrees of Freedom	15DOF	1 DOF			
ER7- Operates with 1-3 standard 120V plugs	1-3 Plugs 360W	0 50W			
ER8- Does not overheat	<75°C	5°C			
ER9- Easy to use	<10 min demo	N/a			
ER10- Reliable use	> 10,000 joint cycles	N/a			
ER11- Accuracy of finger	Within 5mm	N/a			

5 REFERENCES

[1] C. Gordon *et al.*, *Anthropometric Detailed Data Tables*, NCSU Ergonomics Center (excerpts from ANSUR), Apr. 21, 2006 https://multisite.eos.ncsu.edu/.../Anthropometric-Detailed-Data-Tables.pdf

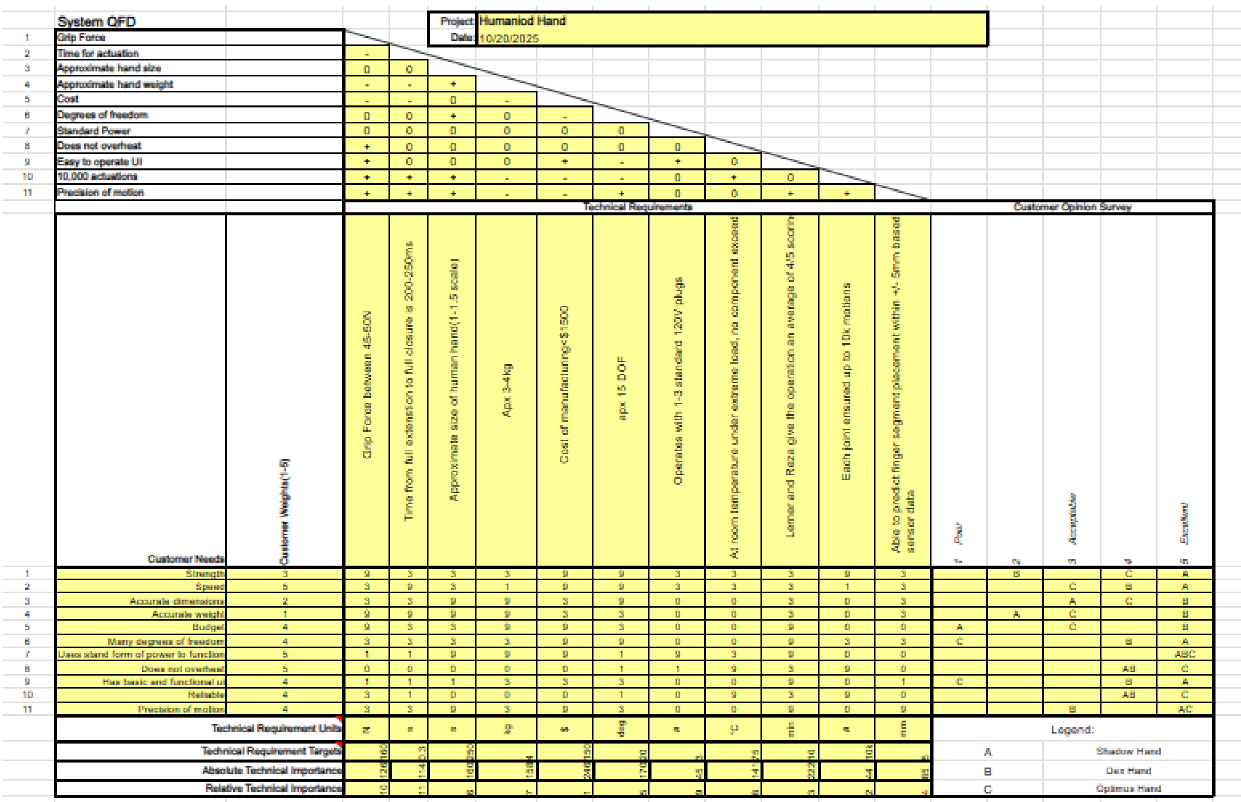
[2] M. Asadujjaman and M. B. A. Molla, "Stature estimation from hand anthropometric measurements," *Procedia Manufacturing / ScienceDirect* (2019). https://www.sciencedirect.com/science/article/pii/S1752928X1830413X

[3] S. Bhuyan *et al.*, "Reliability of Automatic Measurement for 3D Hand Scanning," *Proc. 3DBody.Tech Conf.*, 2020. https://proc.3dbody.tech/papers/2020/2038bhuyan.pdf

[4] D. M. Cristino, *Ph.D. thesis: Lower extremity biomechanical response* ... Virginia Tech, 2018. https://vtechworks.lib.vt.edu/.../Cristino_DM_D_2018.pdf

[5] F. Hundhausen, J. Starke, and T. Asfour, "A Soft Humanoid Hand with In-Finger Visual Perception," *arXiv*, Jun. 5, 2020. https://arxiv.org/abs/2006.03537

6 APPENDICES



System QFD

Project: Humaniod Hand
Date: 10/20/2025

#	Technical requirement	1	2	3	4	5	6	7	8	9	10
1	Grip Force										
2	Time for actuation	-									
3	Approximate hand size	0	0								
4	Approximate hand weight	-	-	+							
5	Cost	-	-	0	-						
6	Degrees of freedom	0	0	+	0	-					
7	Standard Power	0	0	0	0	0	0				
8	Does not overheat	+	0	0	0	0	0	0			
9	Easy to operate UI	+	0	0	0	+	-	+	0		
10	10,000 actuations	+	+	+	-	-	-	0	+	0	
11	Precision of motion	+	+	+	-	-	+	0	0	+	+

#	Customer Needs	Customer Weights(1-5)	Grip Force between 45-50N	Time from full extension to full closure is 200-250ms	Approximate size of human hand(1-1.5 scale)	Apx 3-4kg	Cost of manufacturing<$1500	apx 15 DOF	Operates with 1-3 standard 120V plugs	At room temperature under extreme load, no component exceed	Lemer and Reza give the operation an average of 4/5 scorin	Each joint ensured up to 10k motions	Able to predict finger segment placement within +/- 5mm based sensor data	1 Poor	2	3 Acceptable	4	5 Excellent
1	Strength	3	9	3	3	3	9	9	3	3	3	9	3		B		C	A
2	Speed	5	3	9	3	1	9	9	3	3	3	1	3			C	B	A
3	Accurate dimensions	2	3	3	9	9	3	9	0	0	3	0	3			A	C	B
4	Accurate weight	1	9	9	9	9	3	3	0	0	3	0	3		A	C		B
5	Budget	4	9	3	3	9	9	3	0	0	9	0	0	A		C		B
6	Many degrees of freedom	4	3	3	3	3	9	9	0	0	9	3	3	C			B	A
7	Uses stand form of power to function	5	1	1	9	9	9	1	9	3	9	0	0					ABC
8	Does not overheat	5	0	0	0	0	0	1	1	9	3	9	0				AB	C
9	Has basic and functional ui	4	1	1	1	3	3	3	0	0	9	0	1	C			B	A
10	Reliable	4	3	1	0	0	0	1	0	9	3	9	0				AB	C
11	Precision of motion	4	3	3	9	3	9	3	0	0	9	0	9			B		AC
	Technical Requirement Units		N	s	x	kg	$	deg	#	°C	min	#	mm					
	Technical Requirement Targets		160	0.3	250		150	20	3	75	10	10k	5					
	Absolute Technical Importance		120	114	160	158	246	170	45	141	222	44	85					
	Relative Technical Importance		10	11	6	7	1	5	9	8	3	2	4					

Legend:

A	Shadow Hand
B	Dex Hand
C	Optimus Hand

Figure 1: QFD