United States
Consumer Product Safety Commission

October 10, 2024

CPSC Staff Statement on University of Michigan Transportation Research Institute (UMTRI) "Child Strength Measures: Children 6 through 23 Months Old"[1]

The report titled, "Child Strength Measures: Children 6 through 23 Months Old," presents the results of an in-lab human subjects study on the functional strength of 171 children under 2 years old. Research was conducted in a purpose-built laboratory outfitted with force measurement equipment and test fixtures with toy-like interfaces. Researchers designed 23 exertion tasks including pushing, pulling, and twisting with the hands, and seated and supine push with two feet. Researchers reported summary statistics for measured exertions for boys, girls, and the combined population for five age groups: 6 – 8 months, 9 – 11 months, 12 – 17 months, and 18 – 23 months. Because of challenges with collecting strength data from young children, these data should be interpreted as force levels that children are capable of exerting under the conditions of the study, rather than maximum strength capability; children are likely to be able to exert larger forces than those measured.

Work was completed under CPSC contract 61320618D0004. The purpose of this contract was to expand and update the available strength data for children five years old and younger. Consumer Product Safety Commission (CPSC) staff use data on human strength and capabilities to develop product safety standards and inform other CPSC staff activities. Strength capabilities of children are essential information to incorporate into the design of products that are intended for children to reduce or eliminate the risk such products might pose to a child (e.g., breaking, collapsing, or liberating a small part). In addition, products not intended for children but that can be hazardous to children can be made safer by incorporating performance requirements that consider children's' ability to interact with product components.

The study protocol was approved by a University of Michigan Institutional Review Board for research with human subjects (HUM00158177), and the data-collection protocol was reviewed and approved by the U.S. Office of Management and Budget under the provisions of the Paperwork Reduction Act (OMB Control No 3041-0187).

There are two companion research studies that are being released with this report: "Child Strength Measures: Children 24 through 71 Months Old," and "Bite Force for Children 3 through 71 Months Old."

[1] This statement was prepared by the CPSC staff, and the attached report was produced by the University of Michigan Transportation Research Institute for CPSC staff. The statement and report have not been reviewed or approved by, and may not represent the views of, the Commission.

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Child Strength Measures:

Children 6 through 23 Months Old

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CONTRACTOR INFORMATION

This work was conducted by the University of Michigan Transportation Research Institute for the U.S. Consumer Product Safety Commission under contract number 61320618D0004. The work described in this report was conducted under Task Order 2: Strength Data Update: Strength Measures for Children 6 through 23 Months Old.

The content of this publication does not necessarily reflect the views of the Commission, nor does mention of trade names, commercial products, or organizations imply endorsement by the Commission.

The authors thank the child participants and their caregivers for their patient and valuable interactions. The methods and data presented in this report resulted from the contributions of a large team of talented and dedicated individuals. We are particularly grateful to the data collection team, who patiently refined the methods for working with these young children to generate useful data. The data collection team included: Sarah Rose Beechboard, Miaya Boykin, Laura De Marzi, Thane Deming, Joe McMillan, Alayna Roscoe, Kristina Rowden, and Shinhae (Grace) Yeo. Jamie Moore led participant recruitment, which was critical to ensuring the success of the project.

The laboratory facility and instrumentation were developed specifically for this study and represent a large amount of innovation and creativity. Contributors to the facility and instrumentation included Brian Eby and Jen Bishop. Kyle Boyle contributed to the design of the force-measurement fixtures and Alan Liu produced the engineering drawings of the interfaces.

EXECUTIVE SUMMARY

Data on child force exertion capability are used in the design and regulation of products to enhance safety for children. However, few studies have gathered force exertion data for children younger than 24 months. To address this gap, a laboratory study was conducted with 171 children ages 6 through 23 months. A total of 23 tasks were devised in which children interacted with toy-like interfaces. Forces were measured for push, pull, and twist exertions with the hands and for two-foot seated and supine push exertions. The data were verified using a manual process that involved visual inspection of synchronized force and video data to ensure that the task was performed within the desired range of behaviors. The peak value of a 0.5-second moving average over the course of each valid trial was analyzed. Three trials were attempted in each condition and the maximum value for each subject in each condition was used in the analysis. Summary statistics were computed for boys, girls, and the combined population for each age group. The data for most conditions showed increases in average force exerted with increasing age, but variability was large.

BACKGROUND AND OBJECTIVES

Strength data for children are used to improve the safety of products for children. Regulatory requirements and standards for product safety often cite strength measures. For example, gates used to guard hazards in the home are tested to ensure that they cannot be opened or dislodged by the forces that children in the applicable age range can exert. Currently, minimal information on strength is available for children under two years of age.

A small number of studies have gathered data for children ages two years and older with the intent to develop standards for toys and products for children. Brown, Buchanan, and Mandel (1973, 1974) conducted a study of strength capabilities with the ages two through six years. Owings et al. (1975) conducted a study of the strength of U.S. children, ages 2 through 10 years, with the intention of informing product safety design. Grip strength measurements and upper extremity joint strength of children ages 2 through 10 years were collected as part of a larger study (Owings et al. 1977). Norris and Wilson (1995) published a comprehensive compendium of child anthropometry and strength measures titled "CHILDATA" [sic] that draws on a wide range of sources. This design resource is distinguished from earlier work as it focused on functional measures rather than isolated joint strength as in the Owings et al. work. The age for this resource ranged from birth to 18 years. The U.K. Department of Trade & Industry, Government Consumer Safety Research (2000) conducted a strength study for design safety. Anthropometric and strength measurements were recorded for 150 participants ranging from 2 to 90 years of age including 17 children ages 2 through 5 years.

Few studies have measured strength in children younger than 24 months. Reus et al. (2013) presented children, ages 6 through 36 months, a pull-strength test based on a simulated play scenario. In the context of that work, the team noted that no standardized strength testing methods were available for younger children, and the current literature review uncovered no systematic studies for children less than 24 months old.

A primary conclusion from synthesizing the prior literature in this area and careful consideration of child development patterns is that a rich dataset of functional strength measures would be valuable for product design and the development of safety standards. The objective of the current study was to develop instrumentation, laboratory fixtures, and protocols to measure functional strength for children 6 through 23 months old and to gather data for a large sample of children.

METHODS

Overview

Developmentally appropriate tasks and procedures were developed for children younger than 24 months. The design of the study was informed by pediatricians and other child development experts, as well as engineers with extensive experience with adult anthropometry and strength testing. The interfaces were designed to be toy-like to capture the child's attention for this largely pre-verbal cohort with a wide range of motor development. This study elicited curiosity driven forces through engaging in play with their caregiver and an investigator, and hence these measurements represent possible, but not necessarily maximal, forces. Summary statistics were computed for the maximum forces exerted by each child in each condition.

Institutional Review Board Approval

The protocol was approved as part of the protocol for the larger strength study by the University of Michigan Institutional Review Board for Health Sciences and Health Behavior (HUM00158177), and the data-collection protocol was reviewed and approved by the U.S. Office of Management and Budget under the provisions of the Paperwork Reduction Act (OMB Control No 3041-0187).

Laboratory Layout

The design of the laboratory for this study placed importance on the engagement and interaction between the child participant and investigator. Upon arrival to the University of Michigan Transportation Research Institute (UMTRI), the child and caregiver were greeted by an investigator at their personal vehicle, who escorted them to the reception area and laboratory facilities. Child-size footprints on the floor highlighted the path to the laboratory, and signage was placed in the hallways leading to the laboratory spaces to help the children feel comfortable. Informed consent was obtained in a child-friendly reception room. The intent of the reception room was to provide an environment that enabled an investigator to engage the child in age-appropriate, play-based interaction and to briefly assess the child's temperament, physical, and verbal development. Figure 1 illustrates the initial engagement at UMTRI and the child-friendly reception room.

The laboratory was designed to help the child feel safe but alert. The color scheme and testing structure were intentionally muted to emphasize the engagement between the child, caregiver, and investigator. The presentation of the measurement apparatus was also minimized to not cause distraction or look scary. In contrast, the interfaces were designed to be interesting and friendly (e.g., toy-like) to capture the child's attention.

The physical laboratory space also ensured privacy and sufficient space. Transparent partitions separated a dedicated rest space from the testing structure for the child participant, caregiver, and siblings. This provided a safe place to take breaks and rest when the testing fixtures were being re-configured, and for caregivers and siblings to watch and support the child participant during a testing session. Figure 2 documents views of the child-friendly reception room and laboratory layout, showing the color scheme, partitioning, and dedicated rest space.

Figure 1. Welcome to UMTRI and reception room.

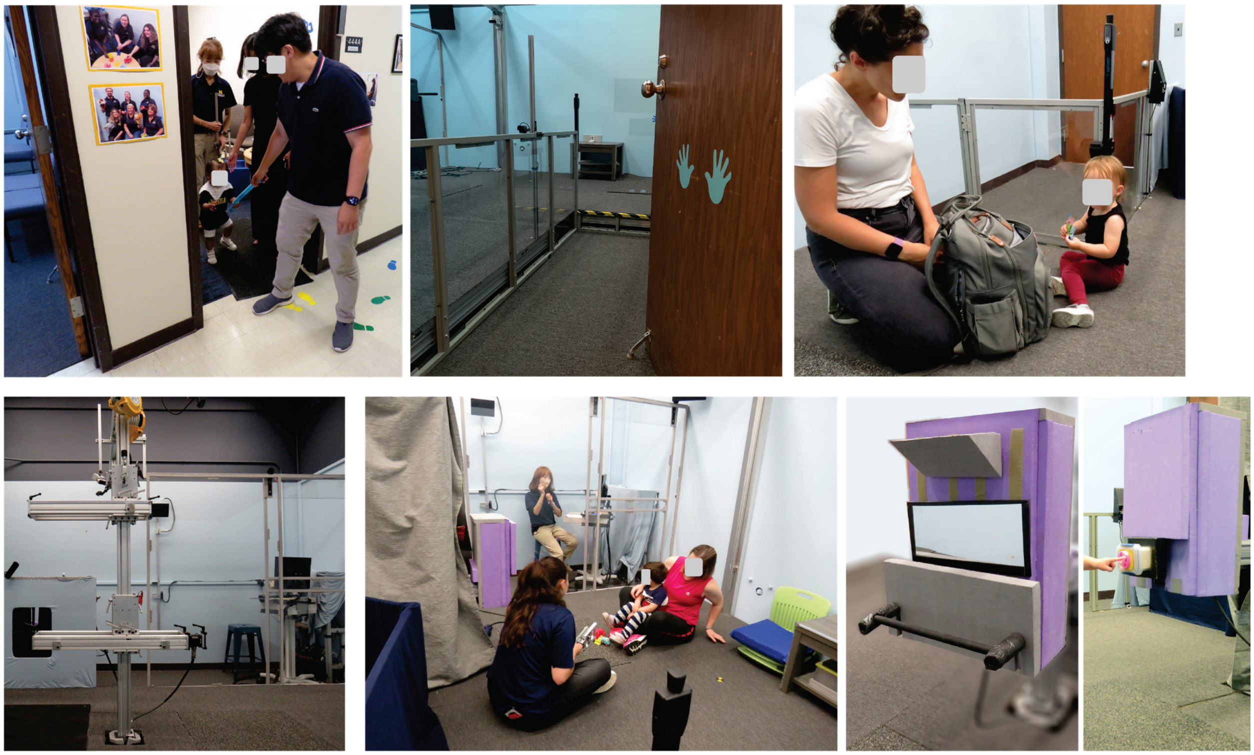


Figure 2. Photos of the laboratory designed for child strength measurement.

Laboratory Fixtures

The laboratory fixtures were designed to enable children to perform functional exertions with application relevance. Importantly, the primary structure was reconfigurable to enable participants to exert forces in developmentally appropriate postures. The fixtures were also highly adjustable to enable the task conditions to be scaled to each child's body dimensions. Laboratory configurations were divided into (1) exertions that involved one or two hands interacting with interfaces mounted to the standing structure and (2) seated and supine exertions with both feet.

The standing structure enabled the vertical and fore-aft location of the handle interfaces to be varied over a wide range (Figure 3). Handle locations were adjustable to the child's body dimensions by means of sliding, lockable components, and counterweighted lifting mechanisms. Standing exertions involved a child participant exerting force with one or two hands on different interfaces that were attached to six-axis load cells mounted on the horizontal sections. The fore-aft position of a horizontal section was set to allow for adequate padding to be applied to the interface and load cell for safety purposes.

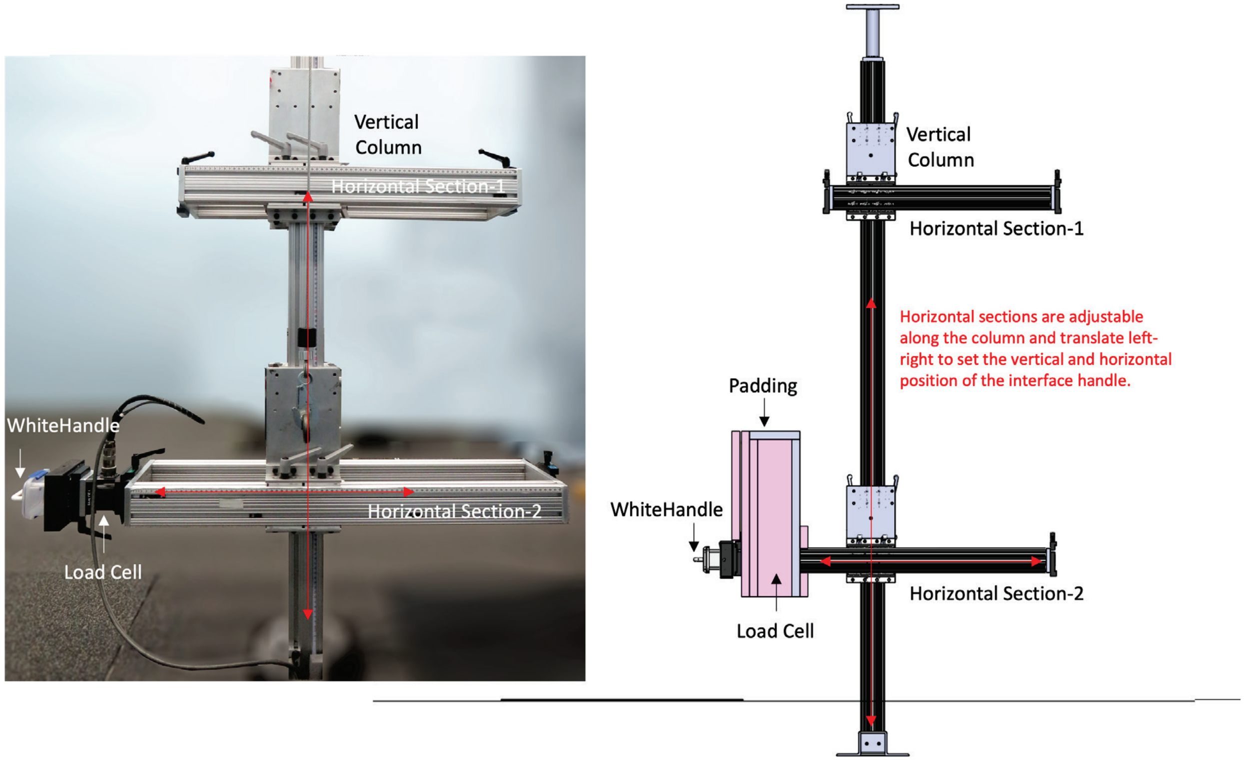


Figure 3. Primary structure components for the push and pull exertions that involve one or two hands. The padding has been removed in the left image to show the load cell. "WhiteHandle" is one of the interfaces used (see Table 2).

A seating fixture was constructed for the feet push measures (Figure 4). The fixture was attached to the standing structure using straps and positioned using a foam wedge. The seat supported the child's posture and positioned them relative to the footboard during the two-feet seated push measure. Two sizes of the adaptive seating system were used to accommodate the size range of children. The same seating fixture, minus the adaptive seating system, was used for the two-feet supine push measure (Figure 5). The horizontal location of the footboard was scaled to the child's body dimensions for both conditions.

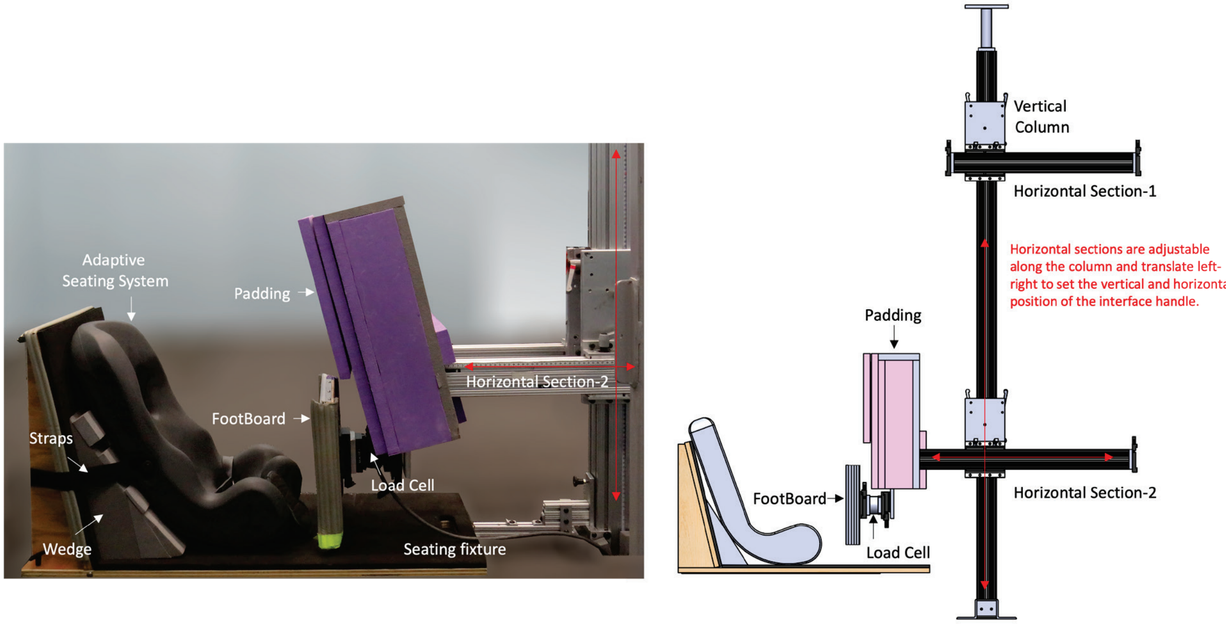


Figure 4. Primary structure components for the seated exertion that involves two feet.

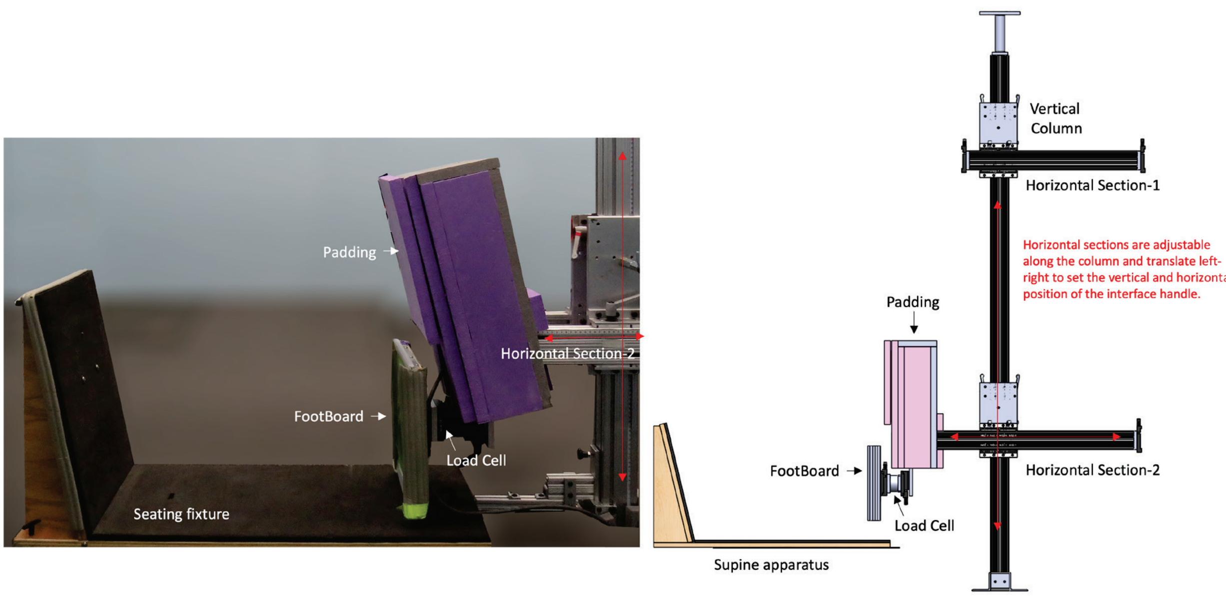


Figure 5. Primary structure components for the supine exertion that involves two feet.

The laboratory included features to improve the safety of the participants and investigators. Safety protocols required child participants be behind the room divider in the “rest space” prior to investigators adjusting or setting the horizontal sections on the testing structure. The adjustable interface features were safeguarded by locking mechanisms, including four locks to secure the vertical position and four locks to secure the horizontal position of each horizontal section with respect to the vertical column. Padding was also applied to the load cells and sharp edges on key components of the testing structure.

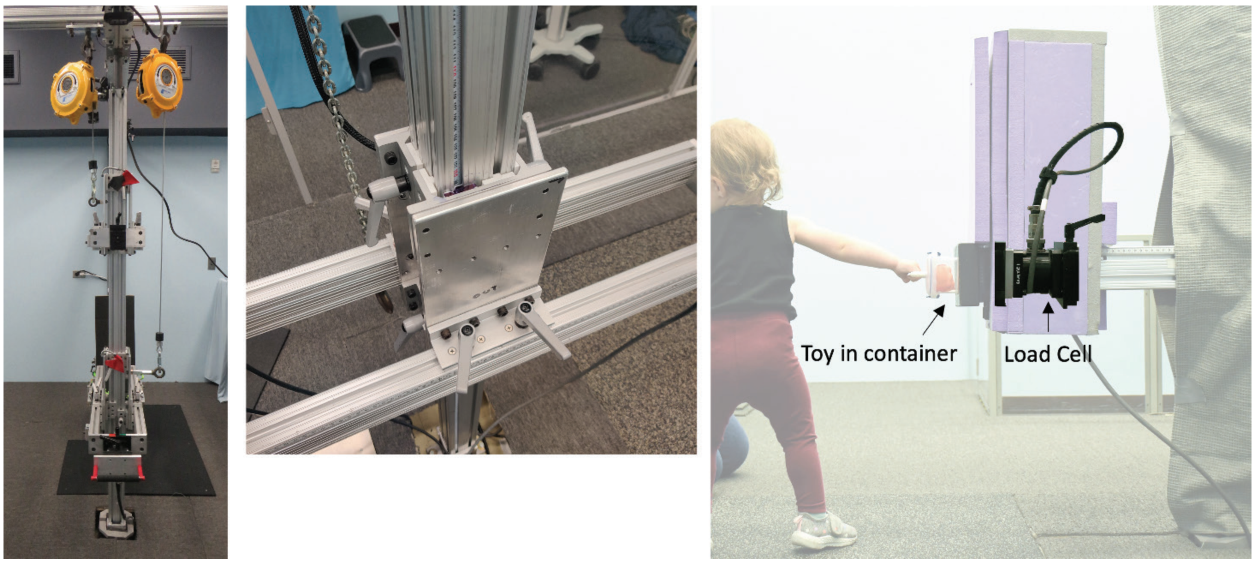


Figure 6. Lift assist devices (left), locking mechanisms (center), and illustration of padding for standing tasks (right)

Instrumentation

Data were recorded using load cells, a force platform, and camera systems. Force data were gathered with both six-axis and uniaxial load cells, with the specific number and combination varying depending on the task being performed (Table 1). The signals from the load cells were recorded and conditioned using a National Instruments cDAQ-9179 chassis and NI9237 bridge input modules. Each data channel was sampled at a frequency of 2000 Hz and filtered digitally using an eight-pole zero-phase low-pass Butterworth filter with a passband frequency of 0-1000 Hz. The load cells were factory calibrated, and crosstalk matrices were used with the six-axis load cells to eliminate errors introduced by off-axis loading. Each load cell signal was verified by suspending an 89 N static mass and ensuring that the recorded force was within 2% of the expected load (Figure 7). Appendix A documents the load cell configurations for the interface handles and individual strength measures.

Table 1
Load Cell Manufacturer, Model, and Capacity

Manufacturer	Model	Capacity*					
		Fx (N)	Fy (N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
AMTI	MC3A-6-1000	2200	2200	4400	110	110	56
AMTI	OR6-7-1000	225	225	4450	1130	1130	565
Denton	3300	12000	12000	14000	450	450	300
Interface	WMC-250	1112					
Interface	WMC-100	445					

* Rated maximum full-scale force on three orthogonal axes (Fx, Fy, and Fz) along with the maximum rated moment around those axes (Mx, My, Mz). The data in this report were gathered on the Fx axis (horizontal pushes and pulls), and the Fz axis (push/pull up/down). Twist exertions were recorded on the Mx axis.

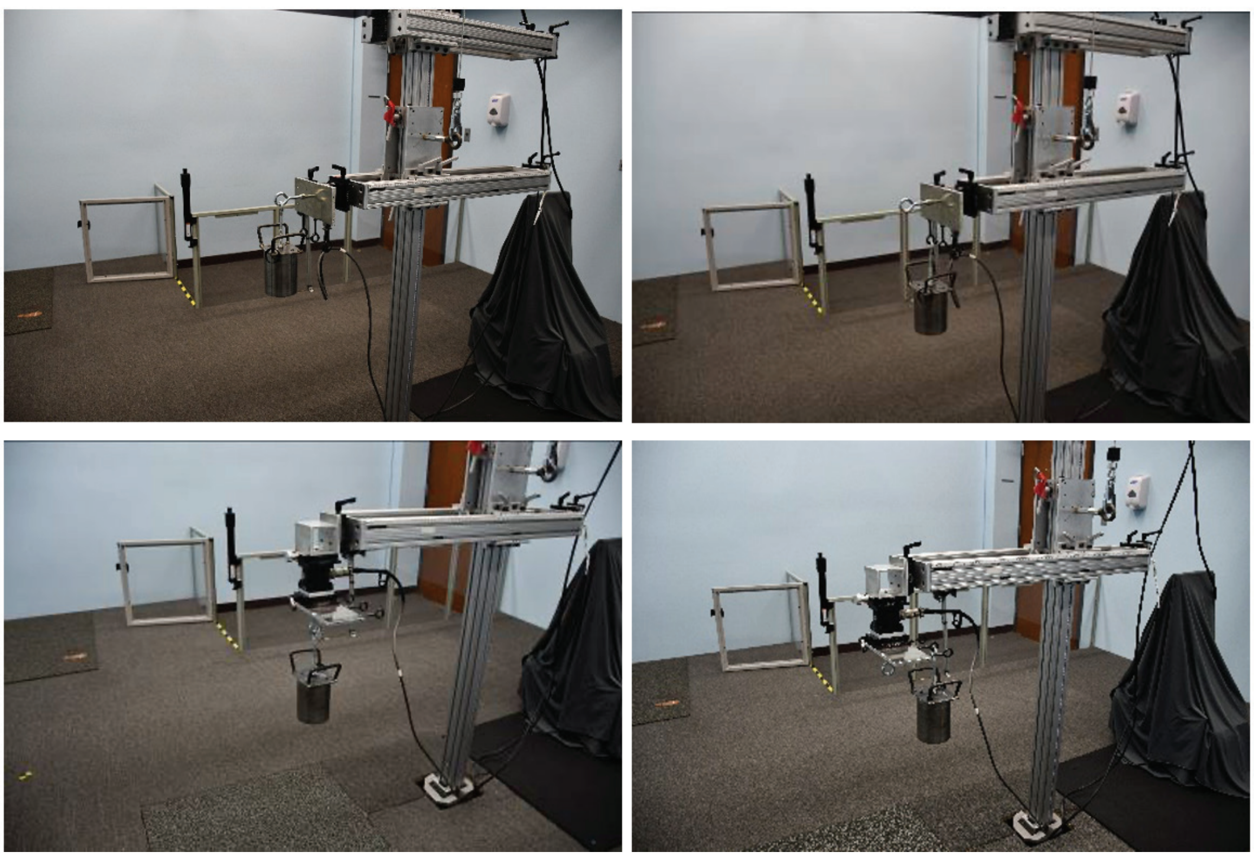


Figure 7. Load cell verification using 89 N static weight. The load cell orientation and weight position were adjusted as needed to verify each force and moment axis.

Interfaces

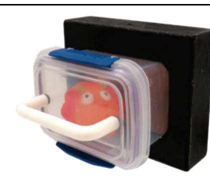
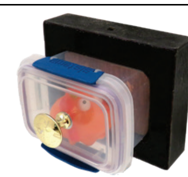
Because children in the age range of interest vary widely in what they find interesting, we created multiple interfaces for similar exertions. For example, we created seven interfaces, ranging from a cylindrical handle to cloth, to elicit one and two-handed pull forces. Our investigators used this variety to find the tasks and toy interfaces that each child would be willing to explore, respond to, aiming to get forces using as many interfaces as possible.

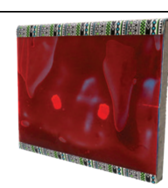
The interfaces were designed to capture the child's attention and communicate (to the extent possible) the desired exertion, minimizing the need for verbal instructions or mimicry. Also, based on guidance from child development experts and our pilot testing, we determined that the child's engagement with the interface needed to result in an "action" or some kind of reward or feedback (e.g., obtain a toy, cause movement, make a noise). Criteria for selection of the interfaces included the ability to instrument, children's interest in the toy, and the ability to elicit force exertions of interest. Instrumenting small toys to accurately measure forces is very challenging.

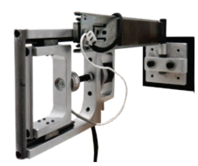
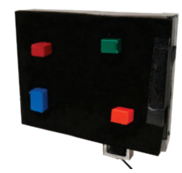
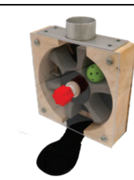
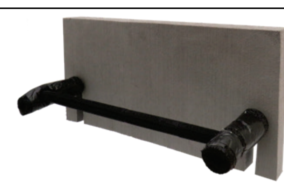
For many of these interfaces, the child was coached or conditioned to explore the interface, perform an action, for example, pulling open a box to reveal a toy. Once they demonstrated the action, the movement of the interface was locked to elicit a high force exertion as the child attempts to complete the action. Using the transparent box with a removable lid allowed a range of push and pull interfaces to be swapped rapidly.

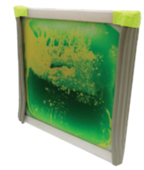
Table 2 lists the interfaces used in this study. Engineering drawings and detailed specifications for each interface can be found in Appendix B.

Table 2
Force Application Interfaces

Interface	Description	Image
WhiteHandle	Cylindrical horizontal plastic drawer handle, 10 mm in diameter with an inner length of 66 mm for hand coupling and 22 mm finger clearance, attached to a transparent plastic container that can be locked to a mounting plate, attached to a six-axis load cell. Locking container to the mounting plate provides resistance to child's force application.	
GoldKnob	Brass drawer knob, with an outer diameter of 28 mm, inner diameter of 8 mm, and 22 mm finger clearance, attached to a transparent plastic container that can be locked to a mounting plate, attached to a six-axis load cell. Locking container to the mounting plate provides resistance to child's force application.	

TissueBox	Toy tissue (200 mm square, 3.8 mm thick) constructed of noise making plastic crinkle paper sewn between two layers of duck cloth. Diagonal corner (113 mm in length) of the toy tissue was presented to child in a fabric tissue box, with the rearmost diagonal corner of the square secured to a plywood mounting plate, attached to a six-axis load cell. Securing toy tissue to the mounting plate provides resistance to child's force application.	
Car	Cylindrical horizontal wooden handle, 43 mm long, 8 mm in diameter, and with 21 mm finger clearance, presented within a wooden toy car, attached to a uniaxial load cell.	
Squishy	Squishy ball toy, 45 mm in diameter, constructed with 2 layers of balloons filled with cornstarch. Squishy ball was held in a nylon mesh pouch, 162 mm in length, attached by a string to a steel universal joint and uniaxial load cell.	
Bubble	Silicone bubble fidget, 50 mm in diameter with 7 individual bubble pop domes each 13 mm diameter and 9 mm of displacement travel, attached to a transparent plastic container that was locked to a mounting plate, attached to a six-axis load cell. A spherical plastic ball bearing (12 mm diameter) placed inside the center dome provided resistance to displacement and force application.	
Bowl	Silicone collapsible bowl, with an outer diameter of 116 mm, inner diameter of 74 mm, and 22 mm of collapsible depth, attached to a transparent plastic container that was locked to a mounting plate, attached to a six-axis load cell. A high-density foam cylinder, 72 mm in diameter, placed behind the silicone bowl provided resistance to force application.	
WhiteHandle_ShapeBoard	Cylindrical horizontal plastic drawer handle, 10 mm in diameter with an inner length of 66 mm for hand coupling and 22 mm finger clearance, mounted to high-density foam. Handle inserted into shape board constructed of plywood and foam and attached to a six-axis load cell. Foam prevented the white handle piece from inserting into the shape board and provided resistance to force application.	
SensoryBoard	A planar gel filled sensory tile (304 mm by 260 mm), mounted on plywood and attached to a six-axis load cell. Non-toxic colorful gel moved with force application.	

Spinner	Spinner toy with fluted pentagon radiused knob with 25 mm radii and 68 mm outer diameter. A uniaxial load cell was integrated in-line with the spinner plunger. Collar added to the plunger to provide resistance force application.	
Dynamometer_24	Custom hand grip dynamometer with the aperture adjusted to 18 mm with 44 mm clearance. A uniaxial load cell was integrated within the fixture. The handle was fabricated with 6061 aluminum alloy. The dynamometer was held by investigators to support the instrument vertically and minimize the potential for application of horizontal force.	
Pegboard	Custom pinch pull fixture with tab interface aperture adjusted to 20 mm. A uniaxial load was integrated within the fixture to measure pinch force and the fixture was attached to a six-axis load cell to measure the pull force. The handle was fabricated with 6061 aluminum alloy and covered in duct tape.	
GearRotation	Fluted hexagon radiused knob with 8.5 mm radii, 39.6 mm outer diameter and 30 mm finger clearance, mounted to an acrylic plate and balsa wood box containing rotating spokes constructed from high-density foam, attached to a six-axis load cell. The turn knob was fabricated with 3D printed polylactic acid plastic (PLA). Locking pin prevented the spindles from rotating and provided resistance to a child's force application.	
PullApart_32	Symmetric plastic knobs, with an outer diameter of 32 mm, inner diameter of 16 mm, and 28 mm finger clearance, asymmetrically mounted to a steel universal joint and wooden cylinder (52 mm in diameter). A uniaxial load cell was integrated with the universal joint, contained within the wooden cylinder, between the two plastic knobs. Total length of the pull apart fixture was 107 mm.	
Bar	Cylindrical horizontal bar, 305 mm long,16 mm in diameter and 58 mm clearance, attached to a six-axis load cell. The bar was coated in vinyl foam that provided a high-friction grip.	
Cart	Cylindrical handle, 248 mm long and 20 mm in diameter, attached to a six-axis load cell. The handle was made of wood and painted with yellow spray paint.	

FootBoard	A planar sensory tile (300 mm square), mounted on plywood and attached to a six-axis load cell. Non-toxic colorful gel moved with force application.	

Strength Measures

Table 3A and 3B list the strength measures by category. Similar to our prior work with adults (Hoffman et al. 2011; Jones et al. 2013), the majority of the task conditions were scaled based on body size. This enabled a focus on the strength of the child, rather than the population capability for the task. (The capability for any population of interest can be determined through subsequent analysis of the data.) However, an additional challenge for the 6- to 23-month-old cohort was that tasks needed to be presented in a manner that spanned a large range of gross motor, fine motor, and muscle strength development. Subsequently, all exertions that involved one or two hands performed relative to an interface mounted on the standing structure (e.g., pull tasks, push tasks, hand strength, and whole-body tasks) were presented to the child either standing, seated on the floor, seated in the caregiver's lap, or seated in a contoured "booster" seat on the floor. For standing postures, the vertical position of the interface was set to 63% of measured stature, approximately elbow height. For seated postures, the vertical position of the interface was set to 90% of seated acromion height, approximately chest height, relative to the surface on which the child was sitting (floor, caregiver lap or booster).

Table 3A
Strength Measures by Category (Pull and Push Tasks, Tug-of-War Pull Tasks, Hand Strength)

Pull Tasks		**Push Tasks**	
White Handle, Pull	BarHandle_Pull	Bubble, Finger, Push	Bubble_Push
Gold Knob, Pull	GoldKnob_Pull	Bowl, Hand, Push	Bowl_Push
Tissue Box, Pull	TissueBox_Pull	Block, Push	ShapeBoard_Push
		Sensory Board, Hand, Push	SensoryBoard_Push
Tug-of-War Pull Tasks		Spinner, Down	Spinner_Down
Car, Tug-of-War	Car_ToW_Pull		
Squishy, Tug-of-War	Squishy_ToW_Pull	**Hand Strength**	
		Dynamometer, 24mm, Grip	Dynamometer_24mm_Grip
		Peg Board, Pinch and Pull	Pegboard_Pull
		Gears, Turn Knob, Clockwise	GearRotation_CW
		Pull Apart, Knob, 32 mm	PullApart_Knob_32mm_Pull

Table 4B
Strength Measures by Category (Whole-Body Tasks, Seated Task, Supine Task)

Whole-Body Tasks		Seated Task	
Cruising from Bar, Pull	Cruise_Pull	2-Foot, Seated, Push	2F_Seated_Push
Sit to Stand, Down/Pull	SitStand_Pull		
Prone, Assisted Pull	Prone_AssistedPull	**Supine Task**	
Dynamic Bar, Pull	DynamicBar_Pull	2-Foot, Supine, Push	2F_Supine_Push
Dynamic Bar, Push	DynamicBar_Push		
Cart, Pull	Cart_Pull		
Cart, Push	Cart_Push		

In all tasks, the child's caregiver was an integral part of the activities, encouraging the child, holding the child during an activity, or engaging with the apparatus (for example, playing "tug of war"). The test matrix also included several additional whole-body exertions, such as pulling up on a bar, that don't fall cleanly within the other categories. In one of these tasks, we asked the caregiver to pick up and pull the child away from the bar that they were gripping as a playful way of eliciting a force exertion limited by grip strength.

Figure 8 illustrates the alternative presentations to the one and two hand exertions. Note that some of these photos were staged for purposes of illustration. During data collection, the photo backdrop was not present, the caregiver and investigator were always close, engaging with the participant, providing encouragement (see Figure 2).

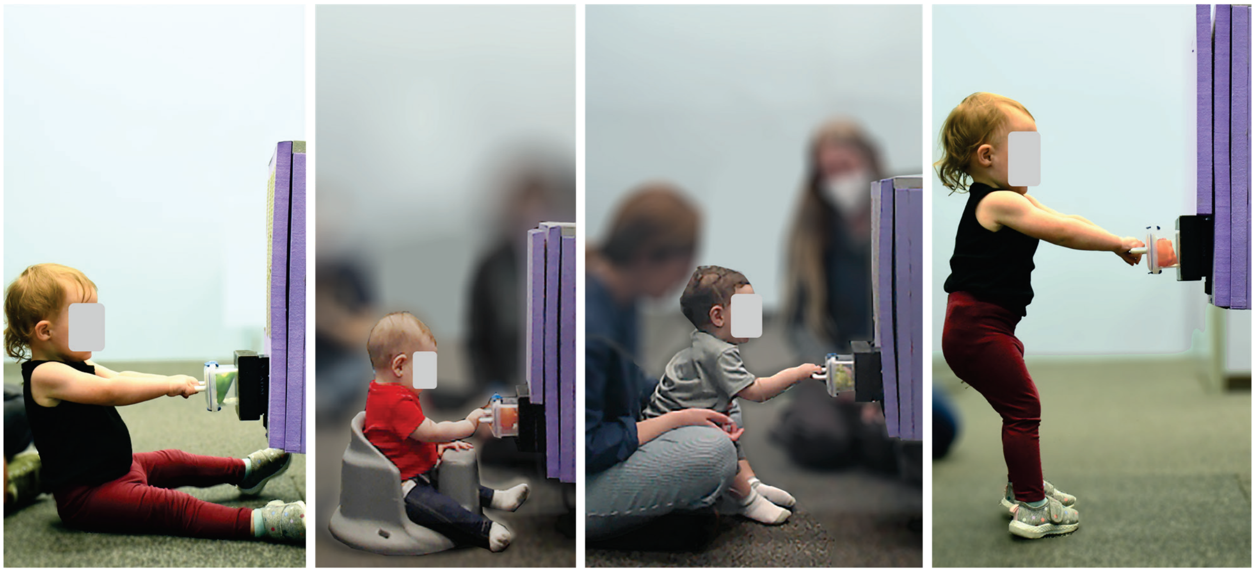


Figure 8. Illustration of alternative approaches to the one and two hand exertions.

Pull Tasks

For both the BarHandle_Pull and GoldKnob_Pull tasks, the caregiver engaged the child in a game of pulling on the container to get the toy or object of interest locked inside (Figure 9). A child's attention was first captured with a toy they liked, and fanfare was made of putting the toy inside the box before closing the lid. The investigator and caregiver initiated a game of opening and closing the container using the handle. The container was then mounted on the standing structure and the child was encouraged to get the container and take out the toy. Next, the child was encouraged to put the toy back in and use the handle to return the container to the standing structure. After several iterations, the investigator locked the container to the mounting plate and the child's pull exertion was recorded. The child was encouraged to pull as hard as they could and to keep trying.

For the TissueBox_Pull task, a game was made of pulling toy tissues from a fabric tissue box. Caregivers and investigators demonstrated by pulling out the red and green toy tissues that detached from the tissue box with ease. The blue cloth tissue, constructed of noise-making plastic crinkle paper, was attached to a mounting plate. Child participants were asked to pull as hard as they could on the pink-blue cloth tissue (Figure 10). Figure 11 shows photos of representative one-hand and two-hand pull exertions.

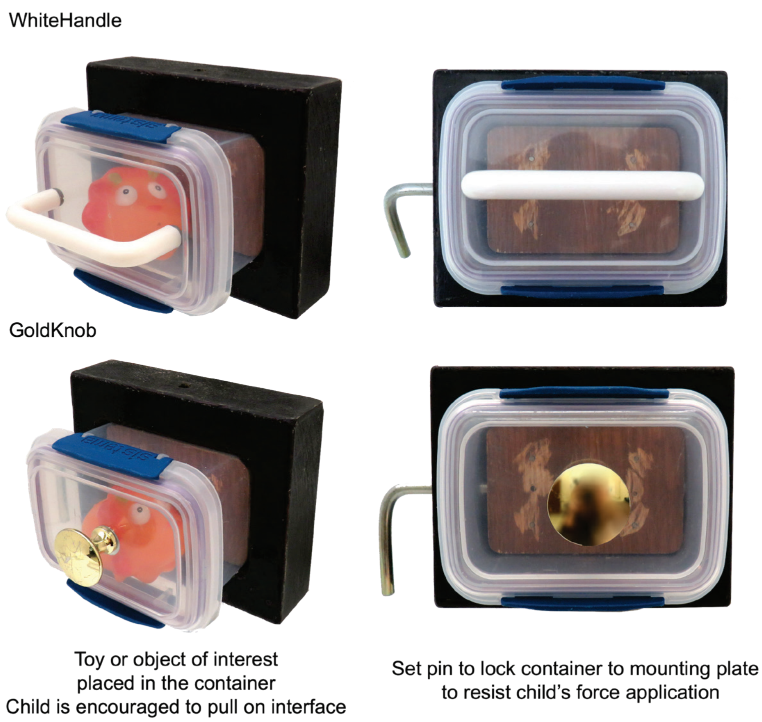


Figure 9. Illustration of the BarHandle_Pull and Goldknob_Pull tasks.

Figure 10. Illustration of the TissueBox_Pull task.

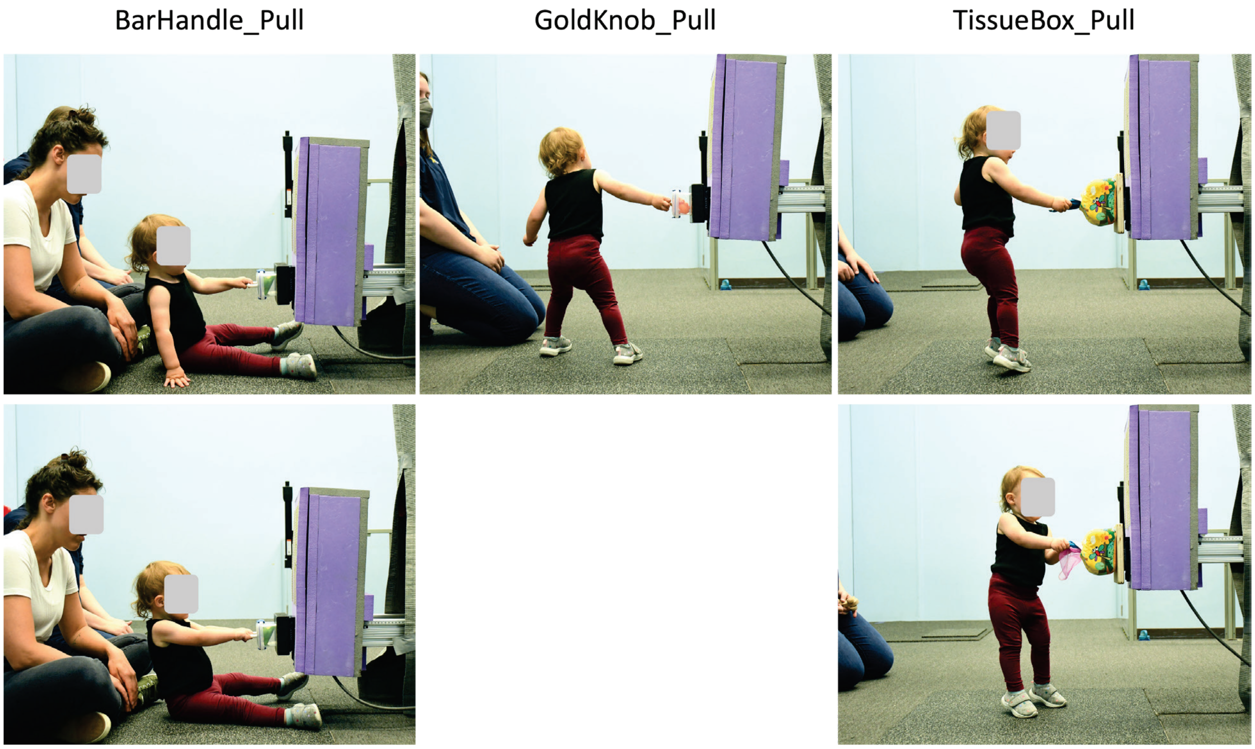


Figure 11. Representative one- and two-hand pull exertions (staged photos for purposes of illustration).

Tug of War Pull Tasks

The Car_ToW_Pull and Squishy_ToW_Pull tasks involved a game of tug of war between the child and investigator or caregiver. Child participants were shown how to hold onto the handle on the wooden toy car and squishy ball. They were encouraged to hang on as tightly and as long as they could and to keep trying (Figure 12). Pulling strength was measured as the object was pulled back and forth between the child and caregiver.

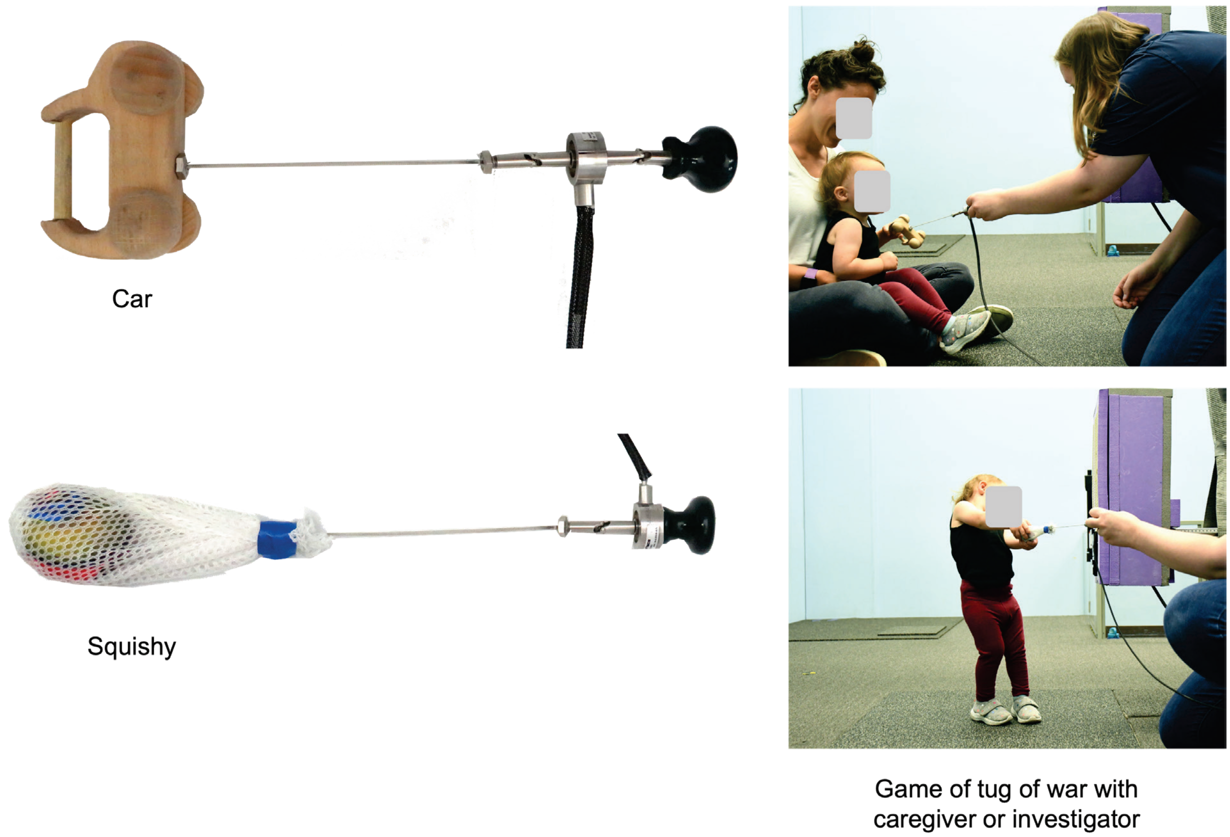


Figure 12. Illustration and representation of the Car_ToW_Pull and Squishy_ToW_Pull tasks (staged photos for purposes of illustration).

Push Tasks

During the Bubble_Push task child participants pushed on and depressed the bubble pop domes. Each individual bubble dome depressed 9 mm, with exception of the center dome that had a spherical plastic ball inside it to resist displacement and force application (Figure 13). Child participants were cheered on to try hard to continue to push and depress the center dome.

For the Bowl_Push, the investigator demonstrated the pushing task with an unmounted bowl on the floor. Child participants were encouraged to press the unmounted bowl with their hands to collapse it (22 mm depth). Once the child was conditioned to the task their attention was directed to a second bowl mounted on the standing structure. This bowl did not flatten all the way, due to a high-density foam cylinder placed behind the silicone bowl to resist the force application (Figure 14). The child was encouraged to try hard to flatten the bowl, ideally with one hand.

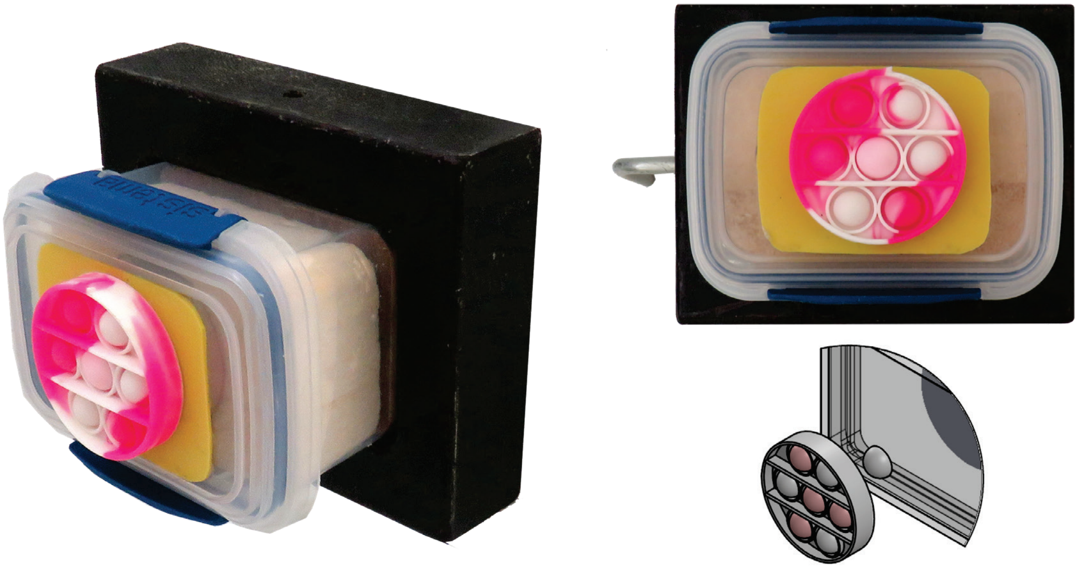
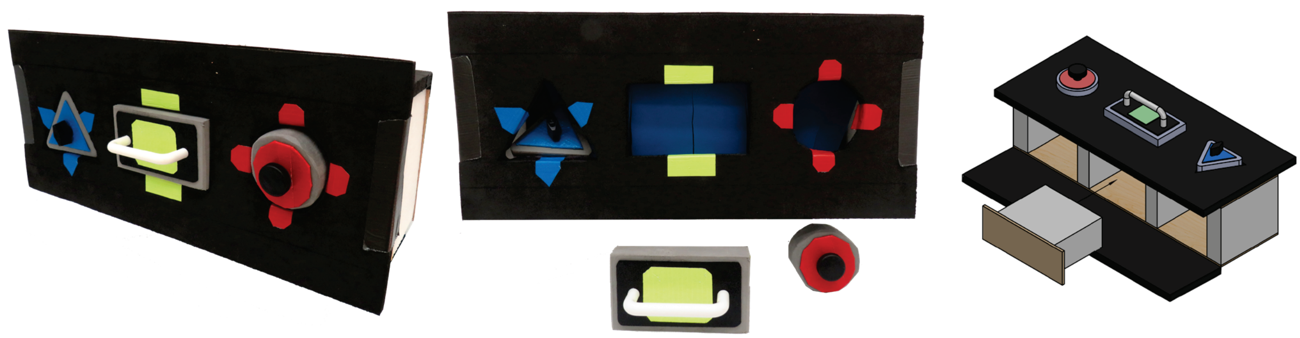


Figure 13. Illustration of the Bubble_Push task.

Figure 14. Illustration of the Bowl_Push task. The center column shows images from undepressed (top) to fully depressed (bottom).

Child participants were encouraged to sort and insert shapes during the ShapeBoard_Push task. Caregivers were asked to help their child with putting the shapes into their respective holes in the shape board. The triangle and circle shapes inserted with ease. Foam prevented the rectangle shape from inserting into the shape board and provided resistance to force application (Figure 15). Child participants were encouraged to push hard on the white handle and try to insert the rectangular shape.

For the SensoryBoard_Push, the investigator demonstrated that an imprint was created when they used their hands to push on the sensory board. Harder pushes created clearer imprints (Figure 16). Stickers located within the gel-filled sensory board also appeared more clearly with higher force application. Child participants were encouraged to push as hard as they could on the sensory board, particularly with two hands. Figure 17 shows photos of representative one- and two-handed push exertions.



ShapeBoard – Child encouraged to sort and insert shapes into the shape board

Foam prevented the white handle piece from inserting into the shape board and provided resistance to force application

Figure 15. Illustration of the ShapeBoard_Push task.

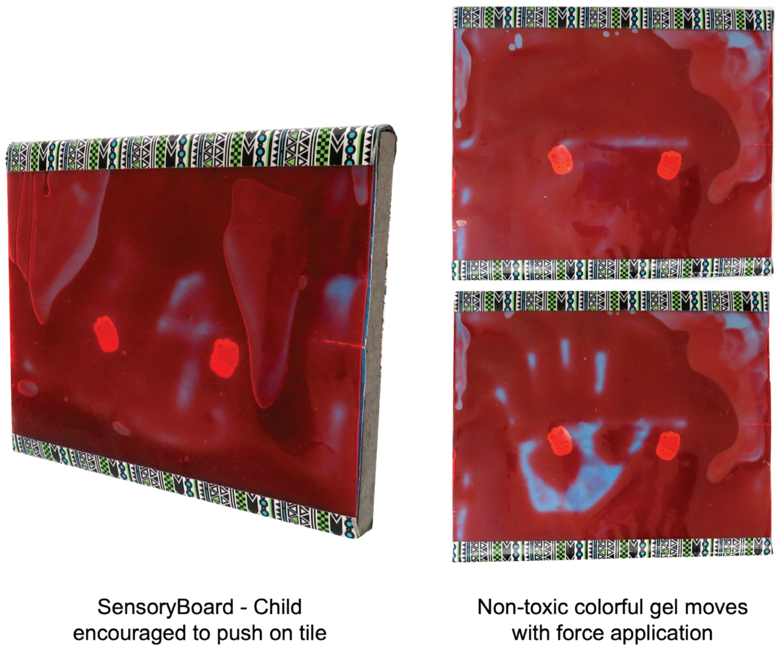


Figure 16. Illustration of the SensoryBoard_Push task.

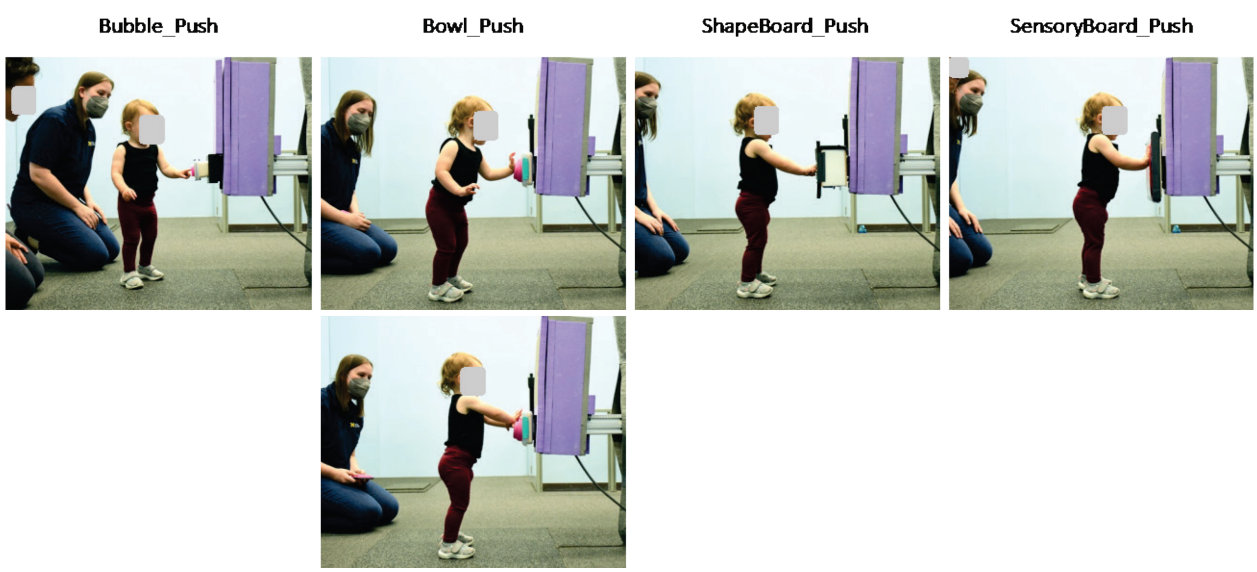


Figure 17. Representative one- and two-hand push exertions (staged photos for purposes of illustration).

For the Spinner_Push task, the caregiver engaged the child in playing with the spinner toy. The caregiver demonstrated that pressing down on the star handle caused the plunger to travel downward, the fish figures and lights within the toy to spin, and music to play. Once the child was conditioned to the task their attention was momentarily re-directed and the investigator added a collar to the plunger that prevented the plunger from depressing and provided resistance to force application (Figure 18). The child continued to be cheered on to push down as hard as they could and to keep trying.

Figure 18. Illustration of the Spinner task.

Hand Strength Tasks

A custom hand grip dynamometer with the aperture adjusted to 18 mm was used to gather grip strength. Although this apparatus was not a toy, it did look interesting and child participants were intrigued. The dynamometer was held by investigators to support the instrument vertically and minimize the potential for application of horizontal force (Figure 19). Child participants were encouraged to squeeze the handle as hard as possible.

For the Pegboard_Pull task, a game was made of pulling pegs out of the interface. Caregivers and investigators demonstrated and engaged the child in pulling out the red, blue, and orange pegs that detached from the pegboard with ease. The green peg could not be removed as it concealed the pinch-pull fixture. Child participants were asked to pull as hard as they could on the green peg in an attempt to remove it (Figure 20).

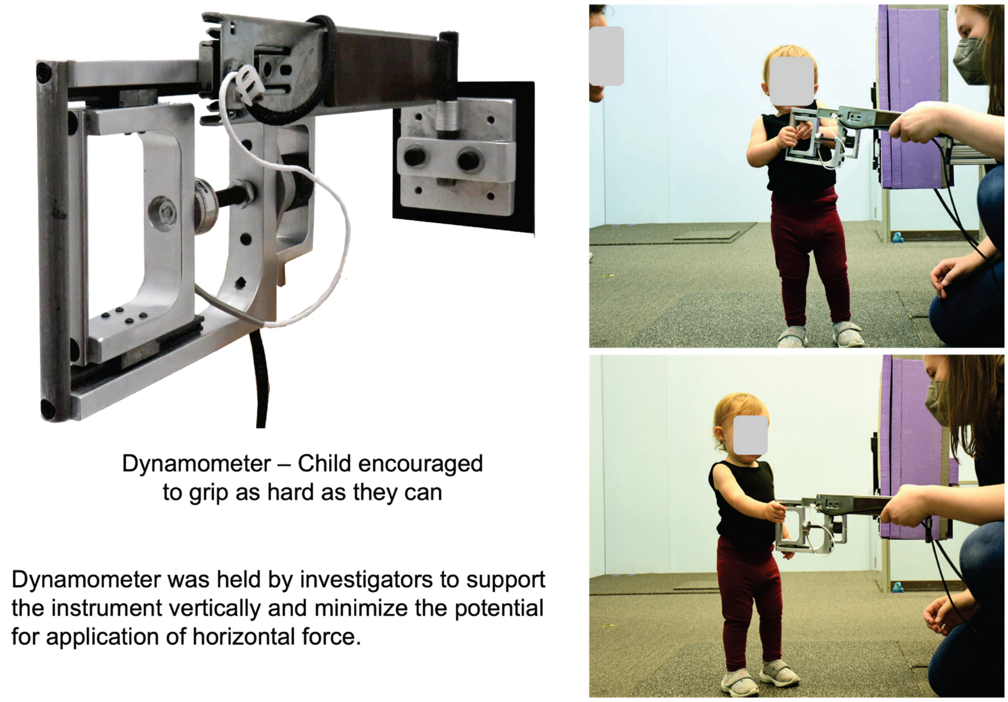


Figure 19. Illustration and representation of the Dynamometer_24mm_Grip task (staged photos for purposes of illustration).

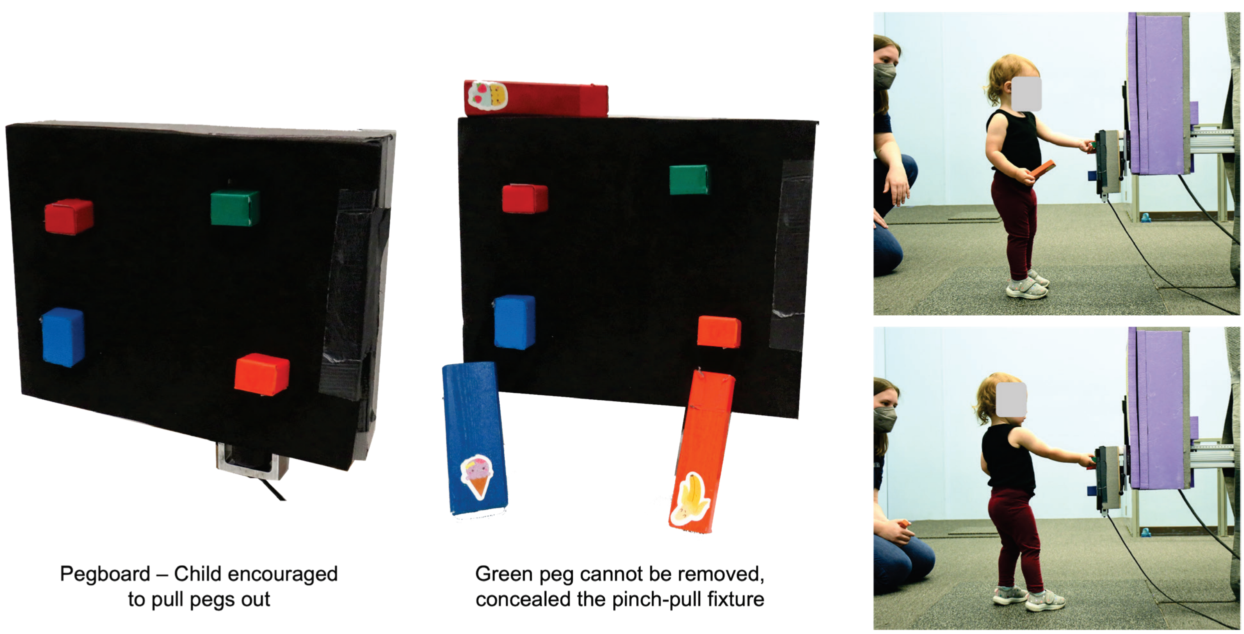


Figure 20. Illustration and representation of the Pegboard_Pull task (staged photos for purposes of illustration).

For the GearRotation_CW task, a child's attention was first captured as the investigator demonstrated putting the ball in the top and turning the knob so that the ball comes out the bottom of the interface. The caregiver and child were encouraged to practice turning the knob and to focus on the ball moving through the gear. After time, the investigator inserted the locking pin to prevent the spindles from rotating and to resist the child's force application. The child was encouraged to continue to try turn the knob as hard as they could (Figure 21).

The investigator demonstrated the PullApart_Knob_32mm task with a practice interface. Child participants used plastic knobs on the pull apart apparatus to open the wooden cylinder. When the child successfully pulled apart the practice interface a crinkle cloth toy was released. Once the child was conditioned to the task their attention was directed to the instrumented interface. Despite their best attempt to pull on the plastic knobs the wooden cylinder would not open. The child was encouraged to continue to try hard to pull apart the apparatus, while holding one knob of the apparatus in each hand (Figure 22).

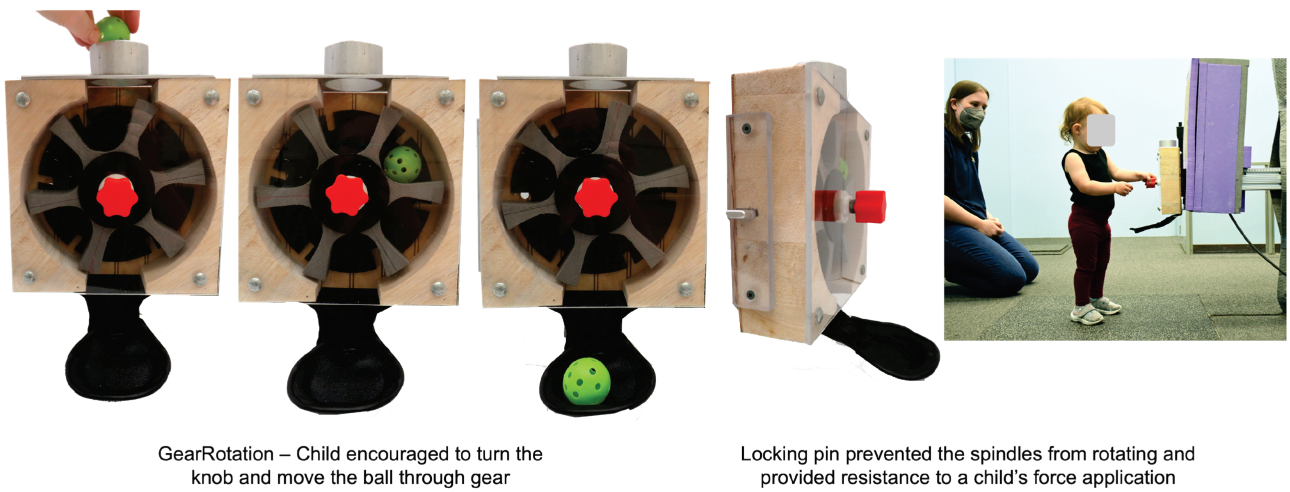


Figure 21. Illustration and representation of the GearRotation_CW task (staged photos for purposes of illustration).

Figure 22. Illustration and representation of the PullApart_Knob_32mm task (staged photos for purposes of illustration).

Whole-Body Tasks

A series of whole-body exertion tasks were conducted using the cylindrical horizontal bar (Figure 23). Padding that was applied to the load cell to which the bar mounted had a dual purpose of hosting a shelf for toys or objects of interest and a mirror to engage the child participants.

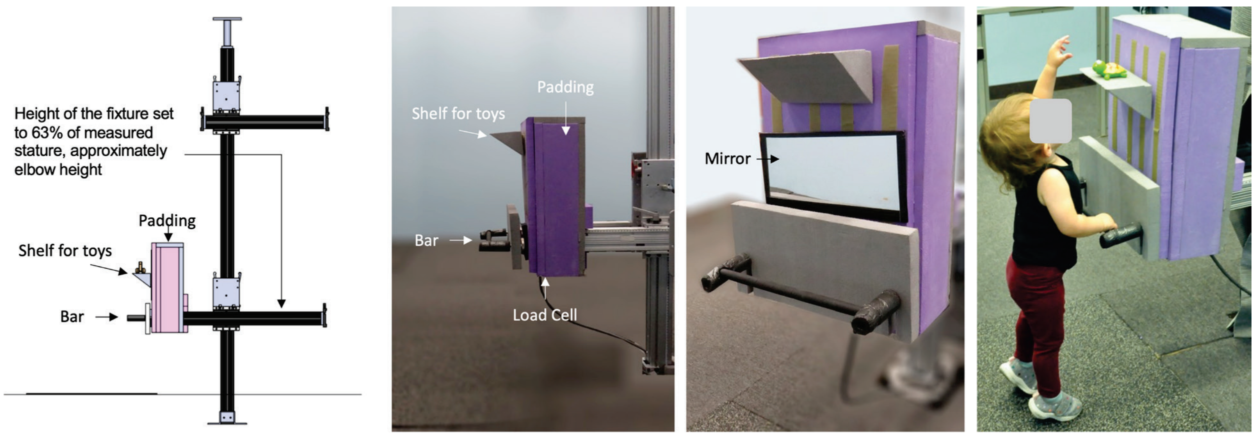


Figure 23. Illustration and representation of the primary structure components for the whole-body tasks (staged photos for purposes of illustration).

The Cruise_Pull task started with the child participant standing with both hands on the bar (if possible). The intent was a game of "keep away" or to gamify reaching for a toy or object of interest. First, the caregiver captured the child's attention with a toy on the child's right side. Then the caregiver would move themselves and the toy away from the child, encouraging them to reach with their right hand for the toy while hanging onto the bar with their left hand. The objective was to see how far they might "pull" on the bar while reaching and moving toward the caregiver and the toy.

The SitStand_Pull task was initiated from a seated posture (on the floor or caregiver lap). The child was asked to use the bar handle to assist in standing up from the seated posture. Investigators encouraged the child to play with the bar handle to acclimate to the whole-body task. Toys were placed on the shelf and the child was able to see their own reflection in the mirror, both strategies that were used to motivate the child. The task was repeated several times. Each time the caregiver was asked to start by placing their child on their rear end, seated on the floor, facing the horizontal bar. Summary forces reported for the SitStand_Pull task are the resultant magnitude of force exerted, considering all three axes.

For both the DynamicBar_Push and DynamicBar_Pull tasks, child participants were asked to push and pull on the bar handle. Caregivers and investigators engaged the child by mimicking the push and pull movement. Toys on the shelf and mirror were also used to persuade the child. The child was encouraged to continue to try to push and pull on the bar handle as hard as they could. If the child was not able to conceptualize the push and pull movement, they were encouraged to shake the bar as much as possible. Figure 24 shows photos of representative whole-body exertions.

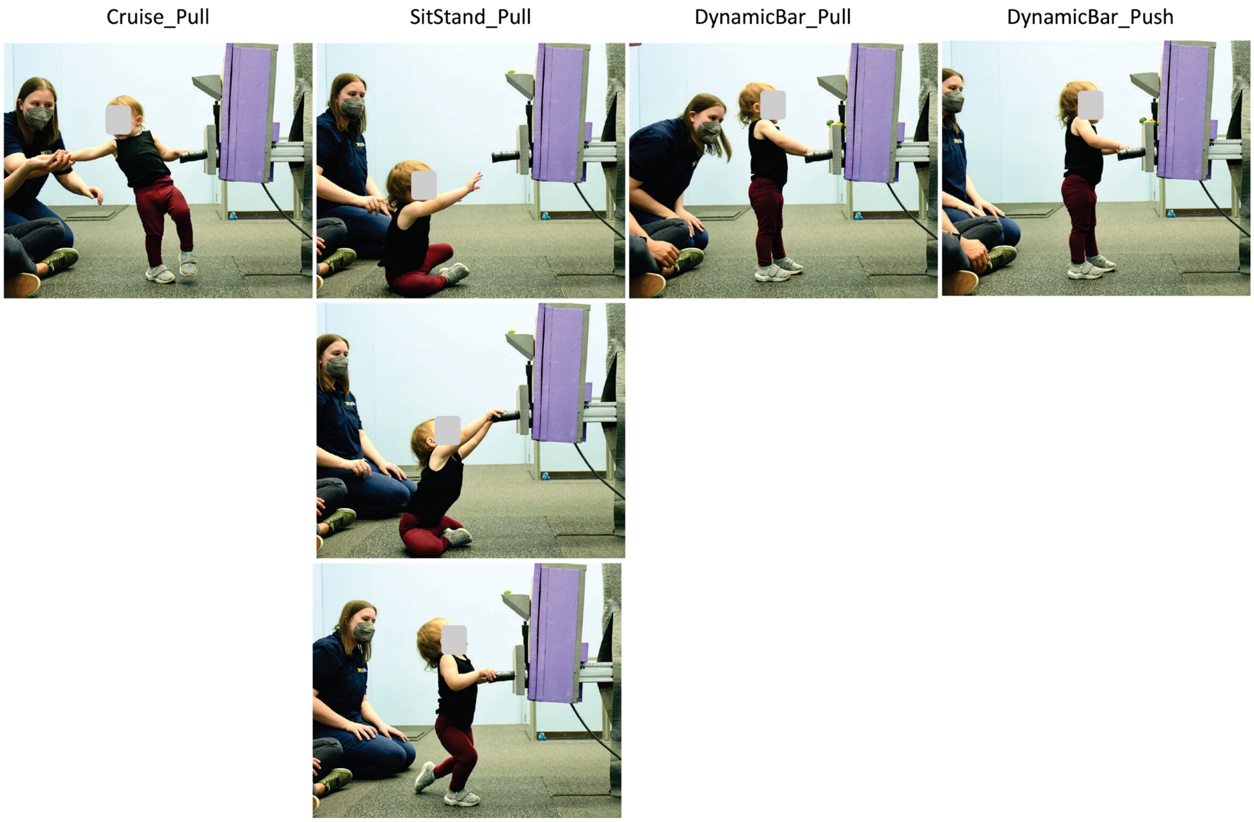


Figure 24. Representative whole-body exertions (staged photos for purposes of illustration).

The Prone_AssistedPull involved asking the caregiver to pick up and pull the child away from the bar that they were gripping (in a flying pose) as a playful way of eliciting a force exertion limited by grip strength. The task was initiated from a standing posture with both hands on the bar handle. Caregivers held their child at their hips or waist. Like the Cruise_Pull task, the assist pull involved a game of keep away, where child participants were encouraged to hold onto the bar as hard as they could and for as long as they could (Figure 25).

The Cart_Push and Cart_Pull tasks were designed to engage the child with a toy they would have familiarity with. The cart was attached to the standing column and could not be moved. Child participants were asked to use the handle on the cart to try and move the cart free. The child was encouraged to continue to push and pull on the cart handle as hard as they could, ideally with two hands (Figure 26).

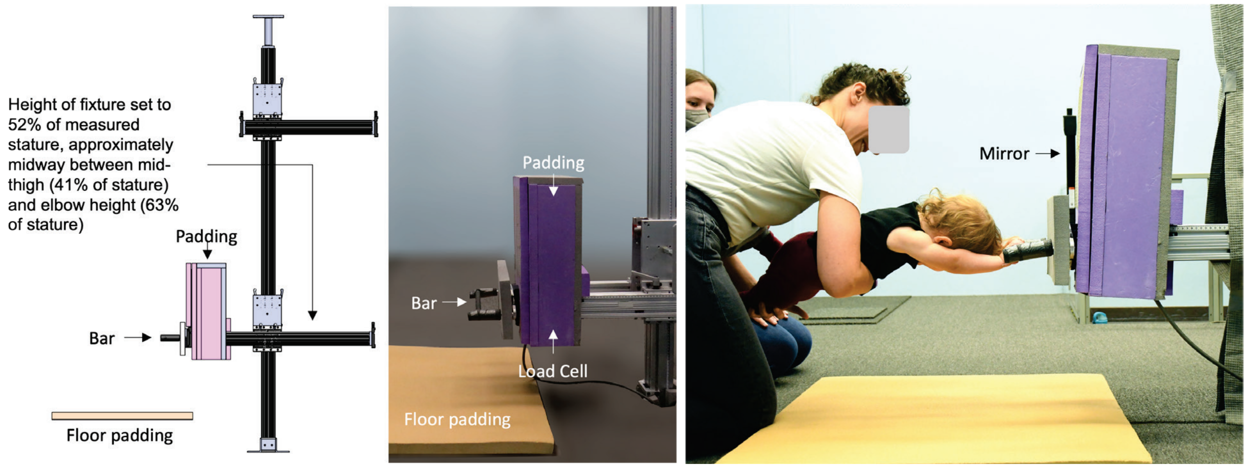


Figure 25. Illustration and representation of the Prone_AssistedPull task (staged photos for purposes of illustration).

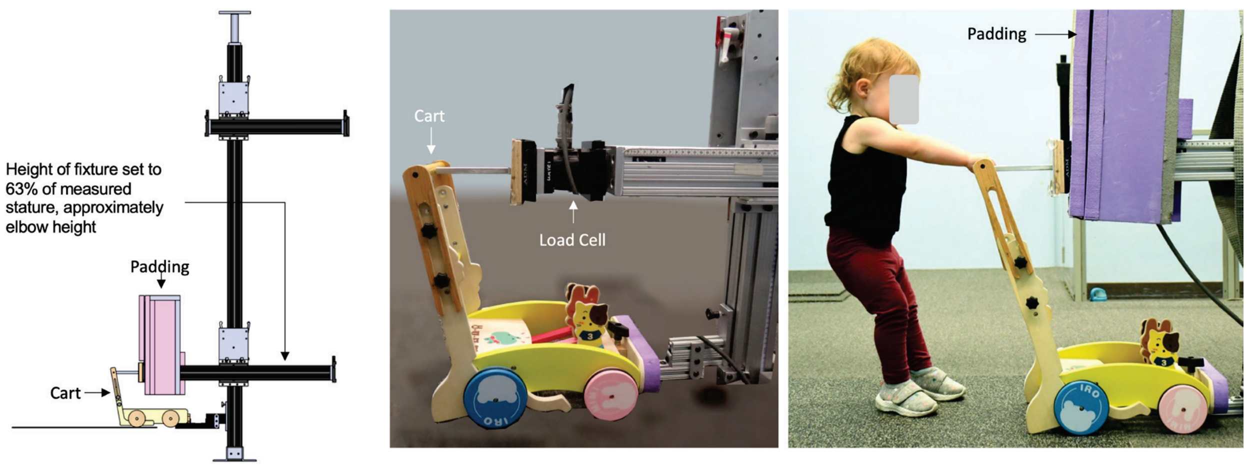


Figure 26. Illustration and representation of the Cart_Push and Cart_Pull task (staged photos for purposes of illustration).

Seated and Supine Tasks

For 2F_Seated_Push exertion, child participants were seated in the seating fixture (see Figure 4). When placing their child in the supported seat, caregivers were asked to place the child's feet flat on the foot board. The horizontal position of the footboard relative to rear of the test seat was set to 95% of the difference between measured stature and predicted erect seated height. This distance was intentionally close and somewhat uncomfortable to motivate the child to push with both feet against the foot board to try to get out. Child participants were encouraged to push as hard as they could. When they pushed, their feet made an imprint on the gel filled sensory board (Figure 27).

For the 2F_Supine_Push task, the participants laid on the seating fixture (see Figure 5). The child was positioned supine with a 90-degree knee angle relative to the foot board surface. The premise was the same as for the 2F_Seated_Push exertion in that the distance was intentionally close and somewhat uncomfortable to motivate the child to push with both feet against the foot board and try and get out. The children were encouraged to push as hard as they could (Figure 28).

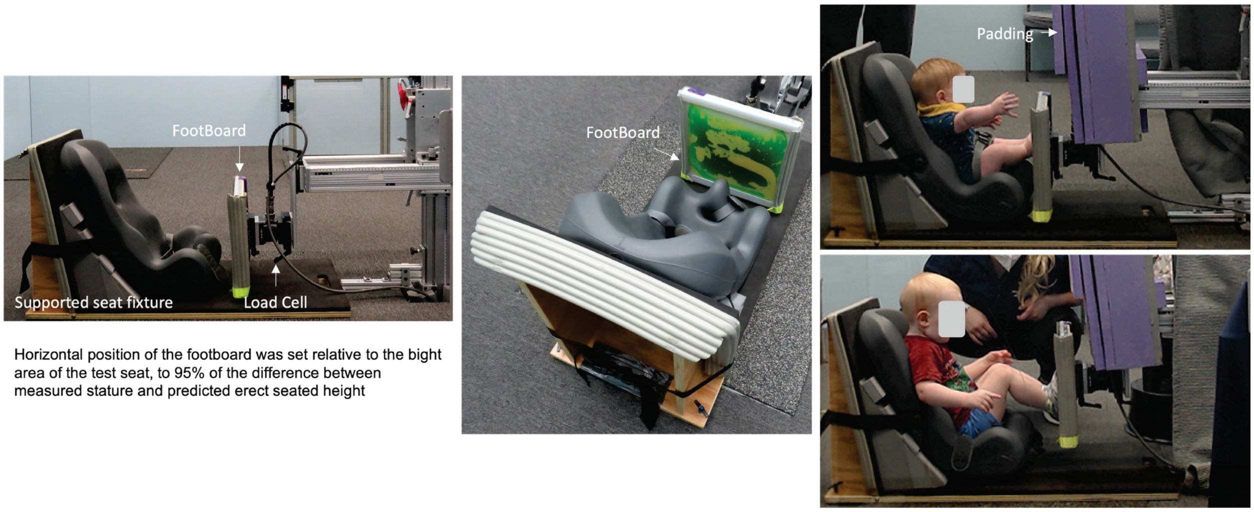


Figure 27. Illustration and representation of the 2F_Seated_Push task.

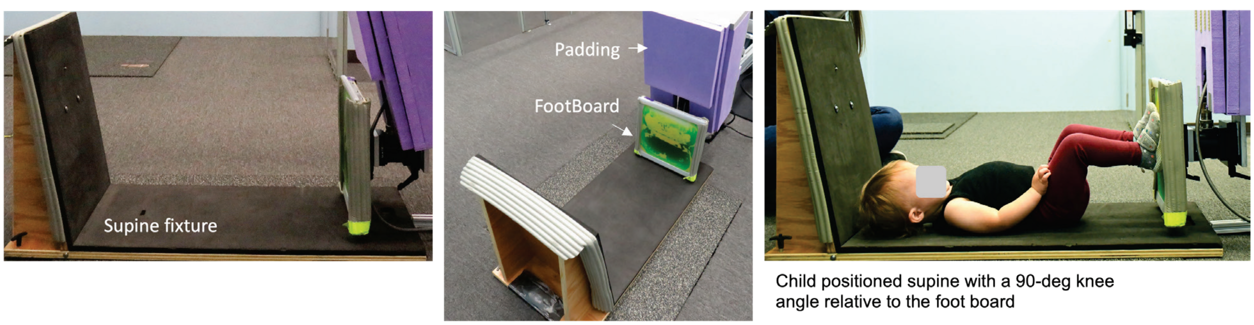


Figure 28. Illustration and representation of the 2F_Supine_Push task (staged photos for purposes of illustration).

The number of exertion tasks for each child was balanced against considerations of motor coordination, attention, motivation, and fatigue. Three matrices were developed to present children with developmentally appropriate task conditions. Table 5 identifies the individual strength measures gathered in the Y1 (12-17 and 18-23 months), B1 (9-11 months), and B2 (6-8 months) test matrices, respectively. Pushing down with one hand on the spinner (measure 10) and the supine foot push (measure 23) were not tested with the older children because they could complete the other one-hand pushes and the seated foot push. Whole-body strength measures were attempted for the youngest age group (6-8 months) only if the demonstrated the ability to stand independently. Similarly, measures that required a hand dexterity and fine motor coordination such as the pulling on the gold knob (measure 2) and rotating the gear turn knob (measure 12) were assessed to not be feasible for the youngest age group. The pull apart (measure 13) was also difficult for the two youngest age groups. A total of 11 conditions were feasible for ages 6-8 months, 22 for ages 9-11 months, and 20 for the two groups 12-23 months.

Table 5
Y1, B1, and B2 Matrices

Measure Number	Measure Description	Interface	6-8 mo [B2]	9-11 mo [B1]	12-17 mo [Y1]	18-23 mo [Y1]
1	White Handle, Pull	WhiteHandle	y	y	y	y
2	Gold Knob, Pull	GoldKnob	N	y	y	y
3	Tissue Box, Pull	TissueBox	y	y	y	y
4	Car, Tug-of-War	Car	y	y	y	y
5	Squishy, Tug-of-War	Squishy	y	y	y	y
6	Bubble, Finger, Push	Bubble	y	y	y	y
7	Bowl, Hand, Push	Bowl	y	y	y	y
8	Block, Push	WhiteHandle_ShapeBoard	N	y	y	y
9	Sensory Board, Hand, Push	SensoryBoard	y	y	y	y
10	Spinner, Down	Spinner	y	y	s	s
11	Dynamometer, 24mm, Grip	Dynamometer_24	y	y	y	y
12	Peg Board, Pinch and Pull	Pegboard	a	y	y	y
13	Gears, Turn Knob	GearRotation	N	y	y	y
14	Pull Apart, Knob, 32mm	PullApart_32	N	N	y	y
15	Cruising from Bar, Pull	Bar	a		s	s
16	Sit to Stand, Down/Pull	Bar	a	y	y	y
17	Prone, Assisted Pull	Bar	a	y	y	y
18	Dynamic Bar, Pull	Bar	a	y	y	y
19	Dynamic Bar, Push	Bar	a	y	y	y
20	Cart, Pull	Cart	N	y	y	y
21	Cart, Push	Cart	N	y	y	y
22	2-Foot, Seated, Push	FootBoard	y	y	y	y
23	2-Foot, Supine, Push	FootBoard			s	s
		y: Measured	**11**	**22**	**20**	**20**
		a: Attempted if child demonstrated ability to stand independently	**6**	**0**	**0**	**0**
		N: Not feasible	**6**	**1**	**0**	**0**
		s: Not attempted because these older children can do similar exertions	**0**	**0**	**3**	**3**

The order of conditions was intentionally varied to maintain engagement with the child participant. For example, a hand push (Bubble_Push) was followed by a hand pull (WhiteHandle_Pull). Under certain circumstances, investigators modified the presentation order or skipped measures in response to safety or issues with child engagement. For example, if a child was not keen on play-based tug of war measures, these would be skipped or not attempted until the end of the session.

Data Collection Protocol

During all aspects of the functional strength protocol, safety considerations were given the highest priority. All study team members who interacted with minors participating as subjects completed comprehensive training modules focused on polices and issues related to the health, wellness, safety, and security of children, and consented to background checks. In adherence with best practices for research with children, all research staff interactions with children were witnessed by an adult third party. As such, caregivers were required to accompany their child throughout testing sessions, and a minimum of two research investigators were always present. For this age cohort, caregivers were a critical part of the research team, continually interacting with the child during data collection, sitting on the floor with the child, and often leading an activity or helping the investigator to engage the child with the various interfaces.

The children were required to perform each exertion task at least three times. For each trial, the child was encouraged to exert as much force as they could within the context of their motor coordination, manual dexterity, and cognitive/sensory development.

The motivation environment was positive to enable continual engagement with the child. Interactions between the investigator, caregiver, and child participant were intentional and scripted to enhance reproducibility. Investigators were trained to speak in their natural voice, show enthusiasm, get down to the child's eye level and make eye contact, and to encourage the child with smiles. Excessive praise was avoided because it rapidly loses effectiveness in motivating the child. Importantly, this age cohort generally cannot respond consistently to verbal instructions that might be sufficient for older children.

The number of trials performed depended on the capability and attention of the child, but the maximum duration of a child's participation was two hours. To minimize the effects of fatigue, five-minute breaks were taken as required or at least every 20 minutes to allow the child to relax and play.

Data Acquisition and Analysis

Multiple cameras recorded the child participant performing each task and were used to assess the child's performance, particularly their tactics for achieving the requested exertions. Images were recorded at a rate of 15 Hz and a resolution of 640 x 576 pixels (Logitech C920) or 1280 x 720 pixels (Microsoft Azure Kinect). The specific number and type of cameras used varied by task. Additionally, multiple time-of-flight cameras (Microsoft Azure Kinect) were used to record 3D point clouds of the participant at a rate of 15 Hz and a resolution of 640 x 576 points.

The data from trials with young children are considerably more challenging to process and analyze than those from adults and older children who are able to follow instructions. Video review of every trial was necessary to categorize the postures and to ensure that the force values were obtained in a valid trial. We developed a software interface that allowed investigators to step through the data, viewing the synchronized video and force histories. The software was used to identify time windows containing valid trials with respect to force magnitude, direction (e.g., hand force must exceed 5 N to be considered a valid trial) and posture (e.g., the child must exert force independently with the requested one or two hands and at least one foot in contact with the floor). Figure 29 shows an example of the time-series data for a sensory board push exertion. The central window with a white background is the portion of the data (event window) that the investigators selected as representing a valid trial, based on the hand force data and the child and caregiver behavior, confirmed from video of the trial.

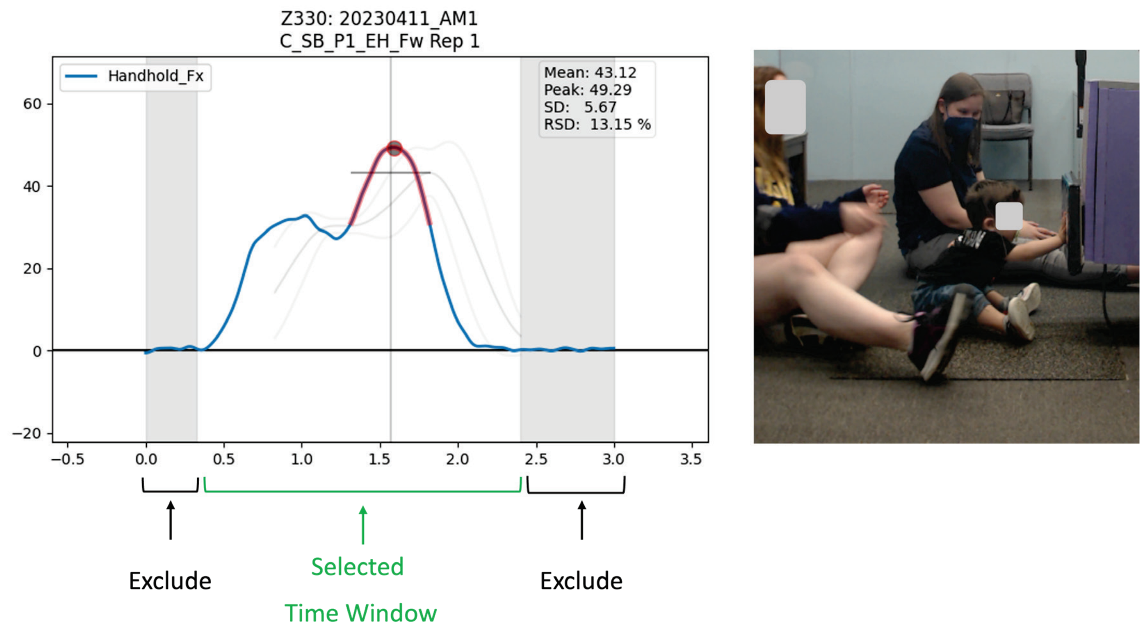


Figure 29. Data verification and window selection (left) for a two-handed push on the sensory board (right). The dark curve on the plot is the force on the desired axis in N. The red circle is the peak force. The red section of the curve is the area in which a 0.5-second moving average reached its maximum value (shown with a horizontal line segment) for the trial.

Peak and moving average metrics were computed over the event window. The identification of the peak value and moving average metrics were independent; the peak value can lie outside of the moving average window. The red circle shown in Figure 29 shows the peak value, and the force-time curve in red illustrates the portion of the data where a 0.5-second moving average was at its maximum. The summary tables in this document report this value as an approximation of maximum sustained force level, the best available estimate of strength.

Only the force value on the requested axis (e.g., horizontal for pushes and pulls) was considered for the current analysis. Note that children usually exerted substantial force on other axes, so that the resultant force magnitude was generally higher than the on-axis force.

The analysis in this report is based on the maximum force observed in the available trials for each participant and measurement location. That is, only the result of a single trial for each participant is included in the analysis for each measure.

Participant Recruitment, Screening, and Consent

Participants were recruited via their caregivers through the University of Michigan Clinical Health Studies website, flyers posted at local childcare facilities, schools, and community centers, social media, and online community bulletin and interest groups. Child participants and their caregivers came to the laboratory and the procedures were reviewed with the caregivers.

Inclusion criteria for the strength study protocol included children ages 6 through 23 months. The children were required to have normal physical and cognitive development. Caregivers were also asked to report if their child was able to follow instructions. These assessments were determined based upon self-reports provided by caregivers during the recruitment process.

Two research investigators initially greeted and introduced the study, one focusing on the caregiver and one to support the child. The procedures were explained and demonstrated using age-appropriate language and methods to both the caregiver and child (e.g., play-based interaction). Written informed consent was obtained using procedures approved by a U-M Institutional Review Board. Oral assent was obtained from children older than 18 months who demonstrated ability to verbally communicate. For children younger than 18 months or who demonstrated a lack of ability to communicate verbally the caregiver was asked to provide verbal consent in the presence of the child participant.

Data from a total of171 children are presented in this report. Table 6 lists the number of children in each age group by gender. Male participants were 54% of the total. Note that not all participants produced valid data for all conditions. The actual number of participants by age group and gender for each outcome measure are presented in the Results section and Appendix D.

Table 6
Summary of the Number of Participants by Age Group and Gender

Age Group	Total	Female	Male
6 – 8 months	17	7	10
9 – 11 months	23	11	12
12 – 17 months	63	24	39
18 – 23 months	68	36	32
	171	78	93

Reasons for Dropouts or Failure to Complete

Strength measures were not obtained in some cases due to a range of issues. Among the possible status outcomes of an attempt to complete the strength protocol were as follows:

1) *Completed*: Strength measures was completed successfully. Note that these trials conformed with the protocol but may not have generated a large force.

2) *Skipped*: The strength measure was not completed for reasons associated with a child's inability or willingness to focus or if the investigators ran out of appointment time to complete the bite protocol.
3) *Attempted*: A strength measure was attempted; however, the child exerted negligible force, the child would not engage in the protocol, or could not complete all three trials.
4) *Refused:* Child or caregiver refused to complete a strength measure.

Participant Characteristics: Anthropometric Measurements

Measurement Considerations

During pilot testing it became apparent that it was not feasible to take all of the desired measurements manually. Two considerations were paramount. First, the measurement time was substantial, more than 15 minutes in some cases, because the children had a hard time sitting or standing still for the measurement. Second, the need to stand still for the measurement was not conducive to the playful attitude and focus that were needed for the strength measurements. That is, taking the anthropometric measures first tended to make the child unwilling to continue to participate in the strength measurement. Taking the measurements at the end was also not feasible because the child was typically tired by that point and unwilling to assume and hold the specified postures.

Consequently, we measured the dimensions listed in Table 7 using definitions and methods based on Snyder et al. (1977). For children who were not able to stand, recumbent length and recumbent torso length were measured in place of stature and erect sitting height, respectively. Acromion height (seated) and maximum reach were recorded for use in scaling test conditions.

Table 7
Anthropometric Dimensions

Dimension	Brief Definition	Method*
Stature (or recumbent length)	Height of top of head above the floor in erect standing with Frankfurt plane horizontal	Anthropometer
Weight	Body weight in normal indoor clothing	Scale
Sitting Height (or recumbent torso length)	Direct measurement	Anthropometer
Acromial Height, Seated	Direct measurement	Anthropometer
Maximum Reach	Standing forward reach, measured to grip center from wall behind child	Marked on wall

* Methods equivalent to Snyder et al. (1977)

Summary Statistics

Table 8 and Table 9 show summary statistics for stature and body weight by gender and age group for all participants. Summary statistics for all anthropometric measures are tabulated in Appendix C.

Table 8
Participant Stature (mm)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	683	44	630	635	678	749	772
6-8	0.50-0.74	F	7	648	16	632	633	642	672	674
6-8	0.50-0.74	Both	17	667	37	630	631	660	725	772
9-11	0.75-0.99	M	12	720	31	671	674	721	761	769
9-11	0.75-0.99	F	11	705	51	628	636	706	777	798
9-11	0.75-0.99	Both	23	713	41	628	645	716	769	798
12-17	1.00-1.49	M	39	764	37	672	716	760	813	852
12-17	1.00-1.49	F	24	734	44	640	675	730	806	809
12-17	1.00-1.49	Both	63	752	42	640	676	755	810	852
18-23	1.50-1.99	M	32	836	43	743	772	834	904	927
18-23	1.50-1.99	F	36	811	38	730	747	808	871	902
18-23	1.50-1.99	Both	68	822	42	730	755	820	899	927

Table 9
Participant Body Weight (kg)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	9.2	1.2	7.8	7.9	8.9	11.0	11.8
6-8	0.50-0.74	F	7	7.5	0.5	6.7	6.9	7.6	8.1	8.2
6-8	0.50-0.74	Both	17	8.5	1.3	6.7	7.2	8.2	10.4	11.8
9-11	0.75-0.99	M	12	9.7	1.1	8.4	8.6	9.3	11.5	11.6
9-11	0.75-0.99	F	11	9.4	1.7	8.0	8.1	8.9	12.7	12.8
9-11	0.75-0.99	Both	23	9.5	1.4	8.0	8.2	9.0	12.4	12.8
12-17	1.00-1.49	M	39	10.5	1.3	8.6	8.7	10.1	12.6	13.8
12-17	1.00-1.49	F	24	9.8	1.4	7.5	7.6	9.8	11.7	12.9
12-17	1.00-1.49	Both	63	10.2	1.3	7.5	8.1	10.1	12.6	13.8
18-23	1.50-1.99	M	32	12.8	1.4	9.6	10.4	12.7	15.1	16.4
18-23	1.50-1.99	F	36	11.2	1.4	8.9	9.2	11.1	13.4	14.4
18-23	1.50-1.99	Both	68	12.0	1.6	8.9	9.4	12.2	14.4	16.4

RESULTS

Summary Statistics

For each measure (e.g., one-hand standing push at elbow height), the mean, standard deviation, and a range of quantiles are presented. Table 10 shows an example summary, listing outcomes for boys, girls, and the combined population by age group. Appendix D provides summaries for all measures.

Table 10
Example Data Summary: HandleBar_Pull, N

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	5	8.0	9.1	1.3	1.4	4.9	20.4	23.3
6-8	0.50-0.74	F	3	4.3	0.6	3.7	3.8	4.3	4.8	4.9
6-8	0.50-0.74	Both	8	6.6	7.1	1.3	1.5	4.6	18.1	23.3
9-11	0.75-0.99	M	9	16.3	5.7	6.9	8.3	16.2	23.6	24.6
9-11	0.75-0.99	F	11	9.2	5.9	0.5	1.1	8.5	17.5	19.8
9-11	0.75-0.99	Both	20	12.4	6.7	0.5	1.7	12.0	22.3	24.6
12-17	1.00-1.49	M	35	16.6	9.1	3.7	5.1	15.8	32.3	41.0
12-17	1.00-1.49	F	21	16.6	10.7	3.2	4.4	14.0	36.0	46.2
12-17	1.00-1.49	Both	56	16.6	9.6	3.2	4.5	14.7	37.1	46.2
18-23	1.50-1.99	M	27	31.9	16.4	5.5	7.5	32.2	58.3	66.8
18-23	1.50-1.99	F	28	20.7	14.2	1.8	3.2	20.2	48.1	56.3
18-23	1.50-1.99	Both	55	26.2	16.2	1.8	4.3	23.1	54.0	66.8

DISCUSSION

Key Findings from the Study

The most important finding from the study is that, through intensive development and investigation, it is possible to gather force-exertion data from young children in a structured manner. Play-based methods built on the children's curiosity and innate tendency for exploration and problem-solving were essential to engaging the children and obtaining useful force exertions. The caregiver was a critical part of the study team, even collaborating on the force exertions (for example, in the tug of war and prone, assisted pull conditions).

Most conditions yielded force data that tended to increase with age. Median values exceeding 20 N were observed for the older children in most of the standing push conditions. Maximum push forces exceeding 70 N were observed for the standing SensoryBoard_Push condition. Grip forces were highly variable and did not show a strong trend with age, suggesting that children were not able to understand what was requested in this relatively abstract task. However, in the prone, assisted pull task, which was grip-strength limited (with two hands), an increasing trend with age was observed and some children exerted forces in excess of 100 N. Cart_Push and Cart_Pull showed no trend with age, suggesting that the fixed-position cart was not eliciting the desired behavior. SeatedFoot_Push produced forces exceeding 100 N for many children, and some children produced more than 300 N. For reference, the mean body weight for the oldest age group (18-23 months) was 129 N (13.2 kg).

Based on observations of the children's behaviors and analysis of the forces exerted, the data gathered are not "strength" in the ordinary sense of the term. That is, all of the children are likely to be able to exert larger forces than those measured in some or all of the conditions. None of the forces were sustained for several seconds, as would be desirable in a typical strength trial. The only reliable way to motivate a child in this age range to produce high forces would be through creating a state of anxiety or fear, which would be unethical. Child participants could also be constrained in such a way where the only way to "leave" is to complete the required exertion although it is unlikely that this approach would be effective for multiple measures. Consequently, these data should be interpreted as force levels that children in the age ranges are capable of exerting under the conditions of the study, rather than maximum capability. Nonetheless, the upper quantiles of these data provide valuable guidance with respect to children's capability, acknowledging that higher forces are possible.

Lessons Learned

1. *Standard strength measurement methods using idealized interfaces and graphical feedback do not work with this cohort*. Our pilot testing revealed that typical strength measurement methods with idealized interfaces and visual feedback based on verbal instructions do not work with this cohort. Hence, new methods were needed.

2. *Interfaces needed to be interesting and friendly, i.e., toy-like*. Observations from pilot studies with this cohort demonstrated that the interface itself needs to capture the child's attention and communicate (to the extent that is possible) the required exertion, minimizing the need for verbal instructions or mimicry. Also, a child's engagement with the interface needs to result in an "action" or some kind of reward or feedback (e.g., toy, causes movement, makes a noise). This poses a major challenge because it is difficult to create instrumented versions of toys. We tried a large number of different potential interfaces before choosing the ones used in this study. Criteria for selection included ability to instrument, children's interest in the toy, and the ability to elicit force exertions of interest.
3. *Most children in this cohort do not understand the idea of a maximal exertion.* Children in these largely pre-verbal stages can't be "instructed", but rather need to be induced to participate in playful activities, driven by their curiosity, that result in them producing forces that can be measured.

Implications and Shortcomings

The study is limited by the sample size, although it is among the largest strength studies that have been conducted with children in this age range. This study used a convenience sample of children and their caregivers from the Ann Arbor area in Southeast Michigan. The results may not be applicable to other populations. All children were reported by their caregivers to have normal development, but no effort was made to verify either cognitive or physical development. Nonetheless, no children with known developmental delays or physical disabilities were included in the sample, which limits the applicability of the results.

The central problem for strength testing in this age range is that these largely pre-verbal children are not motivated to produce exertions outside of play-based activities, and maximum forces are not part of their ordinary repertoire. More generally, most lack the motor coordination and manual dexterity to organize a posture or movement to exert a high force. Children less than 12 months old also lack the cognitive/sensory development to understand cause and effect and hence how to interact with some of the interfaces.

The task conditions include the entire context, which includes the laboratory setup and interfaces as well as the methods used by the investigator and caregiver to motivate the child. These methods were developed in consultation with child development experts and through extensive pilot testing. However, different approaches to the design of the task and motivation of the child could result in different forces.

The children in this study were generally not able to sustain force with low variability for multiple seconds, so these results do not have the character of typical adult strength data, for which the mean of a three-second hold is often used. To address the temporal variability, the maximum value of a 0.5-second moving average was used as the dependent measure. Using a different computational approach would result in different values.

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APPENDIX A: Load Cell Configurations

The following tables specify the load cells used in each condition by matrix.

Table A1
Load Cell Manufacturer, Model, and Capacity

			Capacity*					
Lad Cell Code	Mfr	Model	Fx (N)	Fy (N)	Fz (N)	Mx (Nm)	My (Nm)	Mz (Nm)
A	AMTI	MC3A-6-1000	2200	2200	4400	110	110	56
B	AMTI	OR6-7-1000	225	225	4450	1130	1130	565
C	Interface	WMC-100	445					
D	Interface	WMC-250	1112					
E	Denton	3300	12000	12000	14000	450	450	300

* Rated maximum full-scale force on three orthogonal axes (Fx, Fy, and Fz) along with the maximum rated moment around those axes (Mx, My, Mz). The data in this report were gathered on the Fx axis (horizontal pushes and pulls), and the Fz axis (push/pull up/down). Twist exertions were recorded on the Mx axis.

Table A2. Load Cell Configuration by Strength Measure

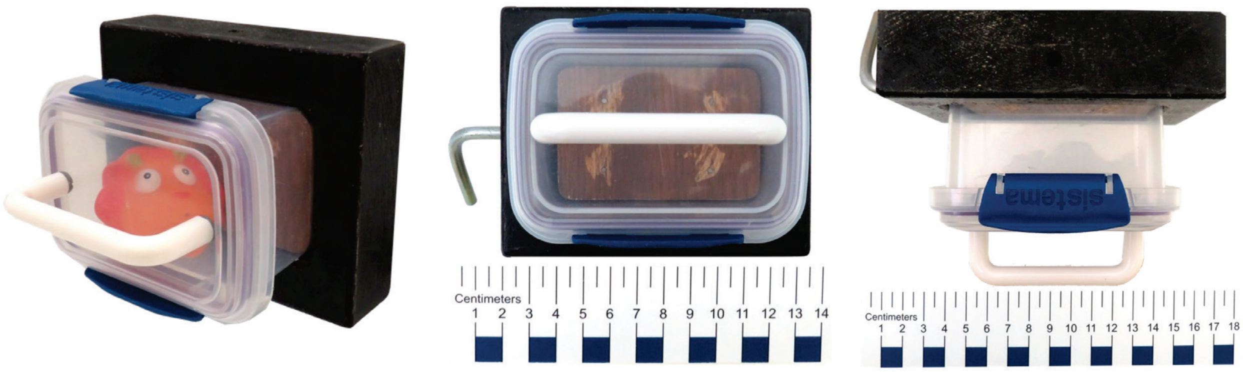
Interface Name	Group	Dir	Primary (Load Cell Code)	Secondary (Load Cell Code)
White Handle, Pull	Pull exertion with one or two hands	Pull	A	
Gold Knob, Pull	Pull exertion with one or two hands	Pull	A	
Tissue Box, Pull	Pull exertion with one or two hands	Pull	A	
Car, Tug-of-War	Pull exertion with one or two hands	Pull	D	
Squishy, Tug-of-War	Pull exertion with one or two hands	Pull	D	
Bubble, Finger, Push	Push exertion with finger, one or two hands	Push	A	
Bowl, Hand, Push	Push exertion with one or two hands	Push	A	
Block, Push	Push exertion with one or two hands	Push	A	
Sensory Board, Hand, Push	Push exertion with one or two hands	Push	A	
Spinner, Down	Downward exertion with one or two hands	Down	D	
Dynamometer, 24 mm, Grip	Grip exertion with one hand	Grip	C	
Peg Board, Pinch and Pull	Pinch-pull exertion with one or two hands	Pull	A	C
Gears, Turn Knob, Clockwise	Clockwise twist exertion with one or two hands	CW	A	
Pull Apart, Knob, 32mm	Two-hand opposed pull	Abduct	D	
Cruising from Bar, Pull	Pull exertion with one or two hands	Pull	A	
Sit to Stand, Down/Pull	Downward exertion with one or two hands	Down	A	
Prone, Assisted Pull	Grip exertion with one or two hands	Grip	A	
Dynamic Bar, Pull	Pull exertion with one or two hands	Pull	A	
Dynamic Bar, Push	Push exertion with one or two hands	Push	A	
Cart, Pull	Pull exertion with one or two hands	Pull	A	
Cart, Push	Push exertion with one or two hands	Push	A	
2-Foot, Seated, Push	Two-foot seated push exertion	Push	A	
2-Foot, Supine, Push	Two-foot supine push exertion	Push	A	

APPENDIX B: Force Interfaces

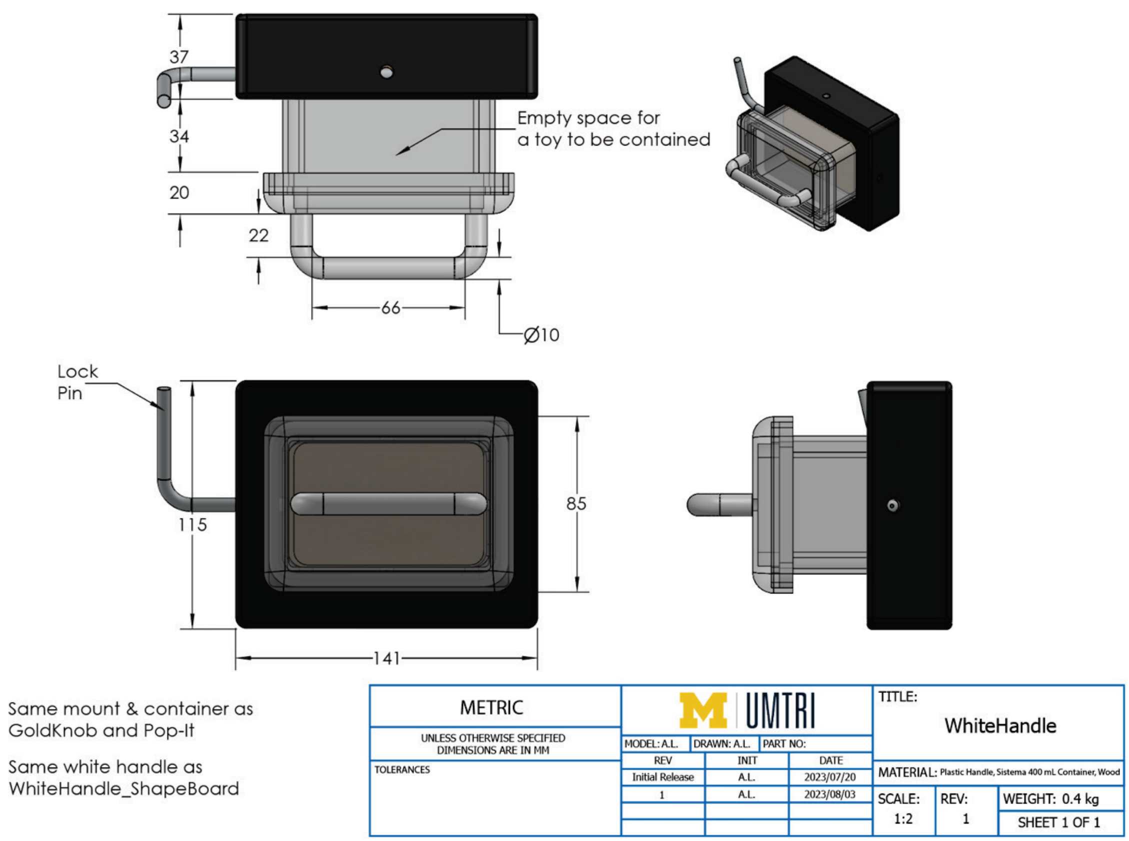
This appendix contains detailed specifications for the interfaces against which the children exerted forces. Photos, dimensions, and materials are provided.

WhiteHandle

Cylindrical horizontal plastic drawer handle, 10 mm in diameter with an inner length of 66 mm for hand coupling and 22 mm finger clearance, attached to a transparent plastic container that can be locked to a mounting plate, attached to a six-axis load cell. Locking container to the mounting plate provides resistance to child's force application.

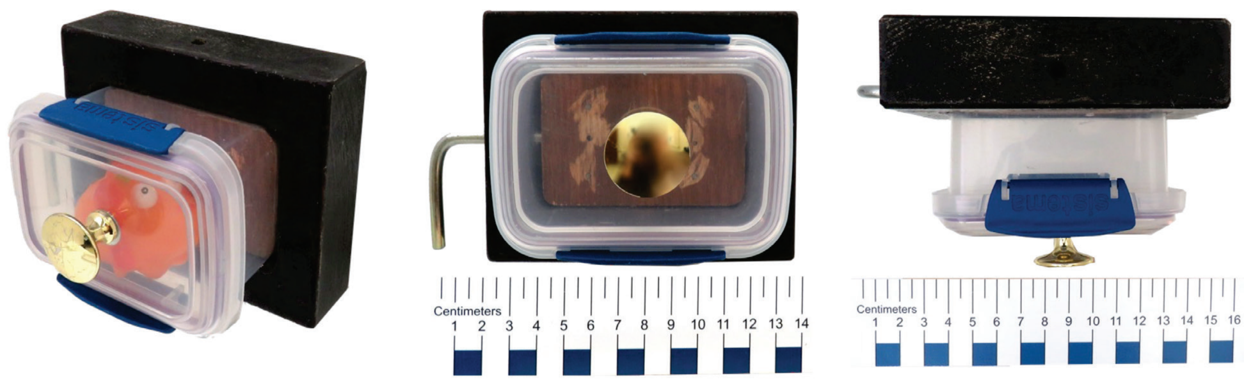


Oblique Front Top

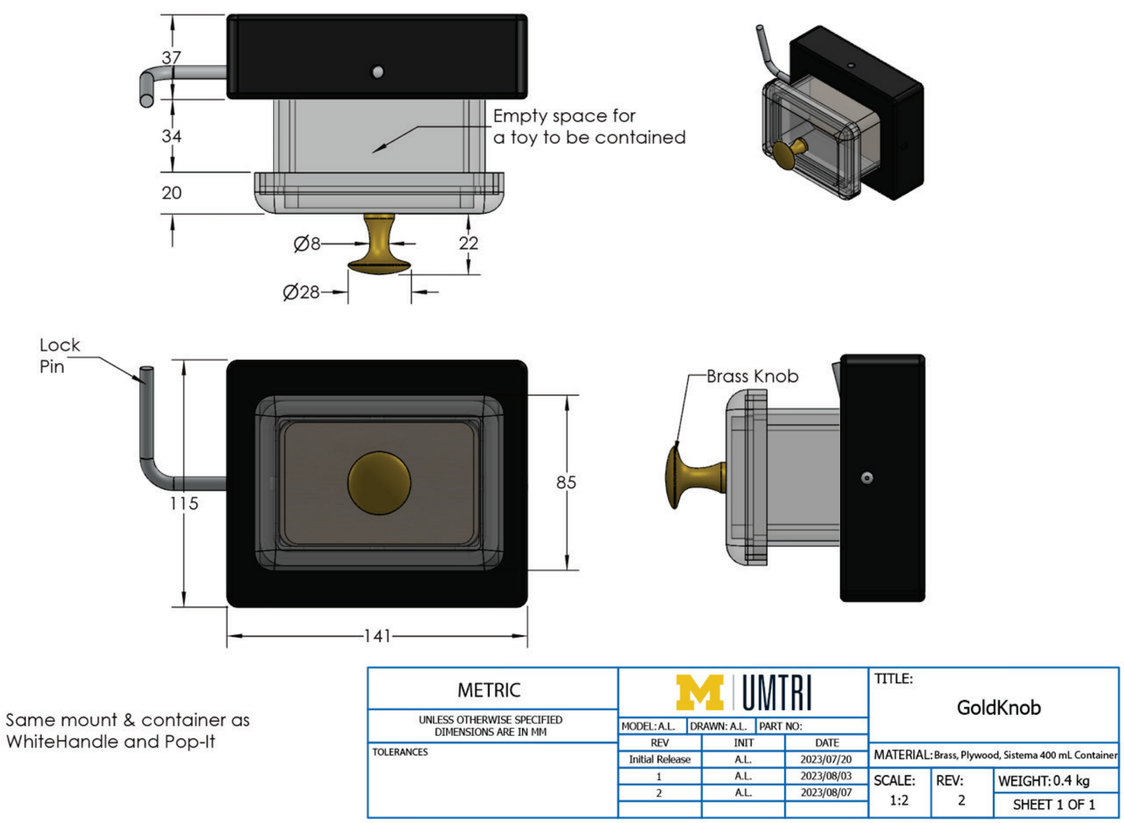


GoldKnob

Brass drawer knob, with an outer diameter of 28 mm, inner diameter of 8 mm, and 22 mm finger clearance, attached to a transparent plastic container that can be locked to a mounting plate, attached to a six-axis load cell. Locking container to the mounting plate provides resistance to child's force application.



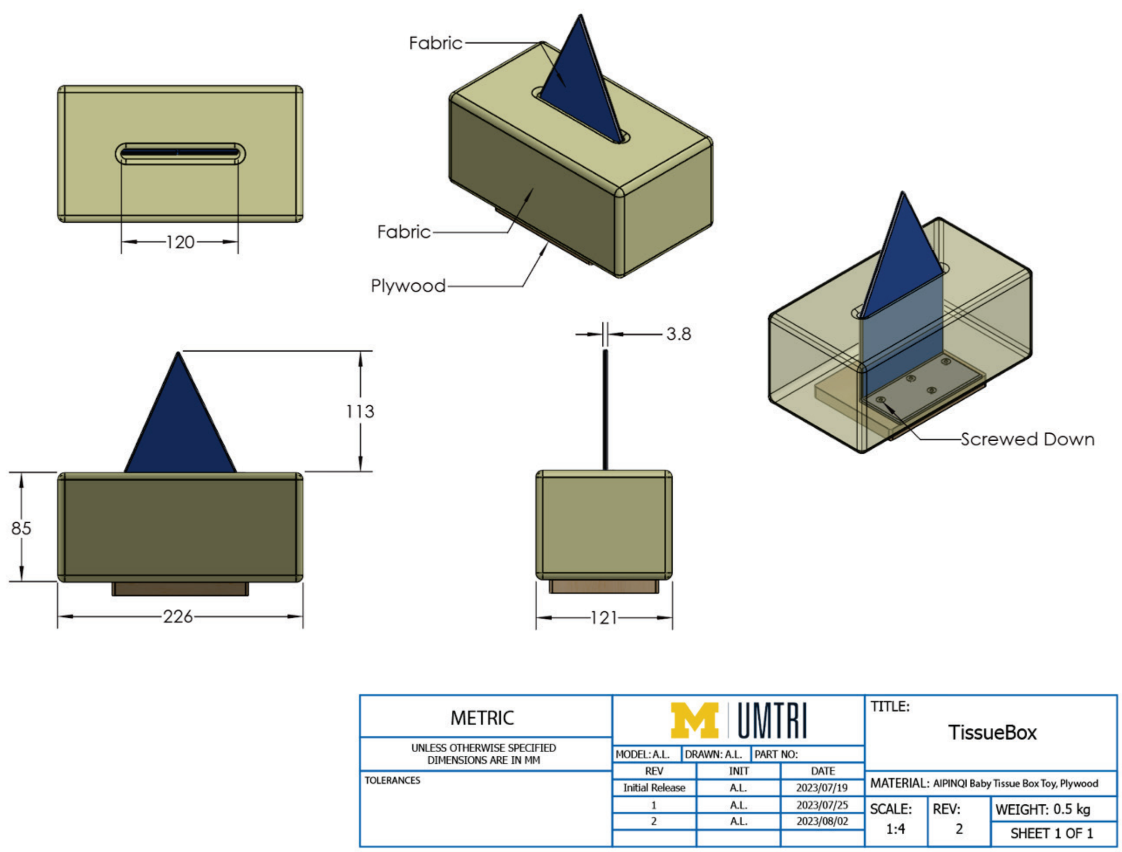
Oblique Front Top



TissueBox

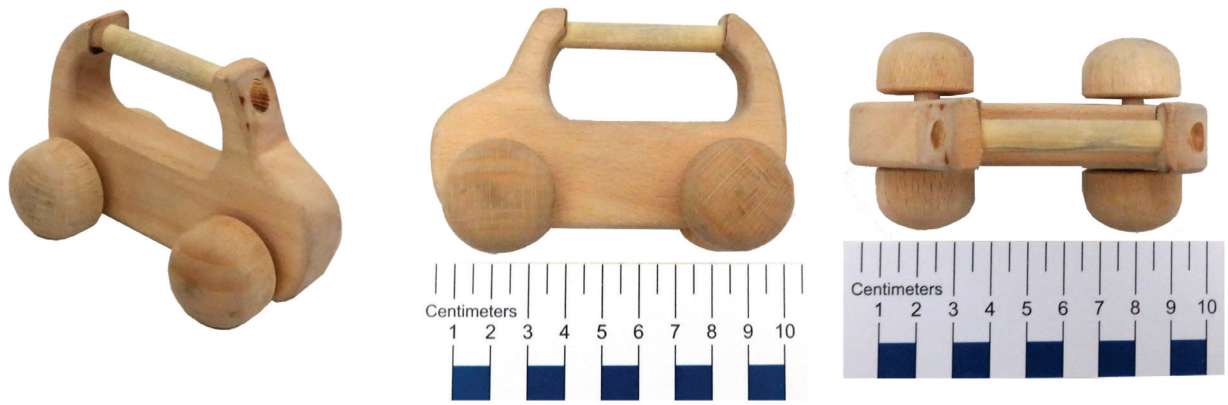
Toy tissue (200 mm square, 3.8 mm thick) constructed of noise making plastic crinkle paper sewn between two layers of duck cloth. Diagonal corner (113 mm in length) of the toy tissue was presented to child in a fabric tissue box, with the rearmost diagonal corner of the square secured to a plywood mounting plate, attached to a six-axis load cell. Securing toy tissue to the mounting plate provides resistance to child's force application.

Oblique Front Top

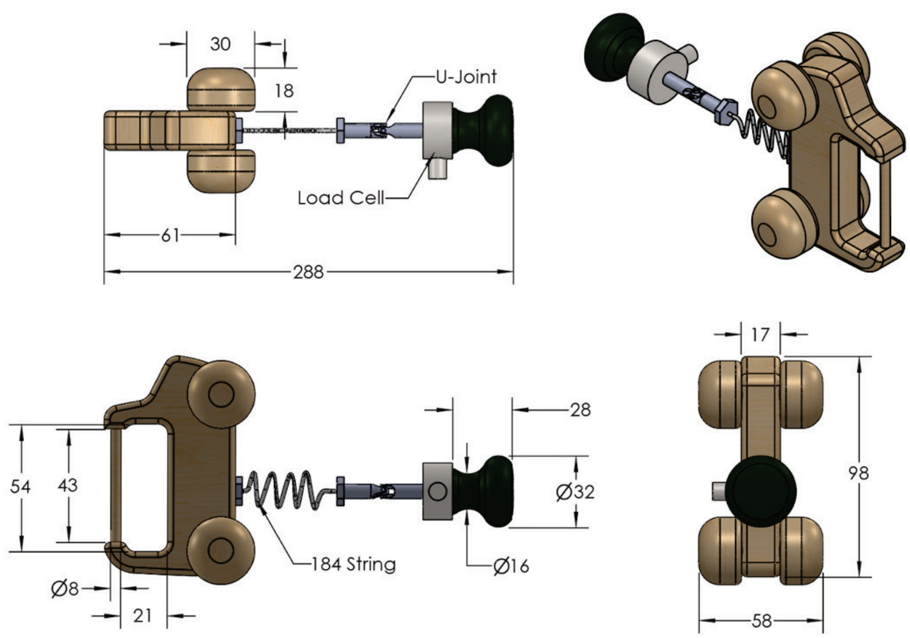


Car

Cylindrical horizontal wooden handle, 43 mm long, 8 mm in diameter, and with 21 mm finger clearance, presented within a wooden toy car, attached to a uniaxial load cell.



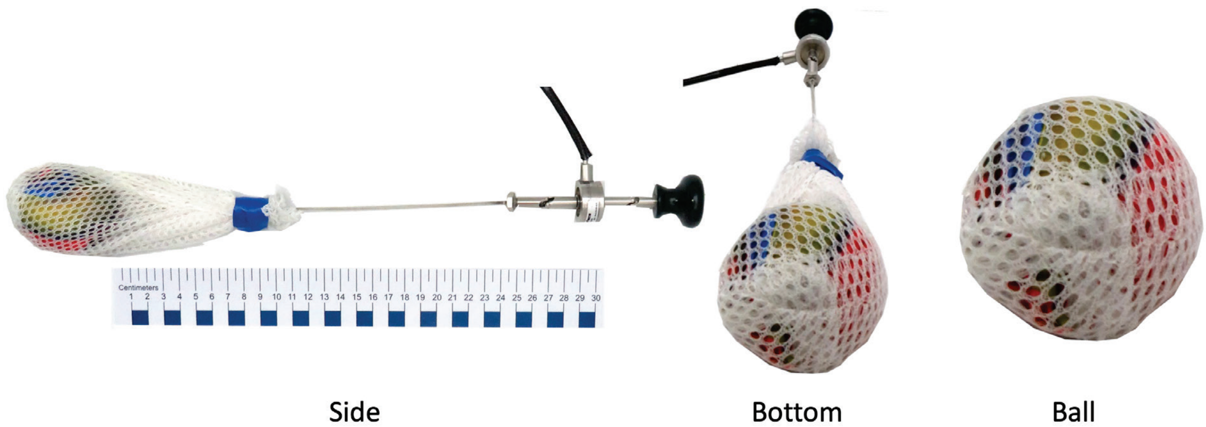
Oblique Side Top

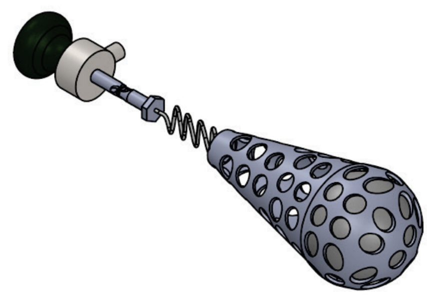


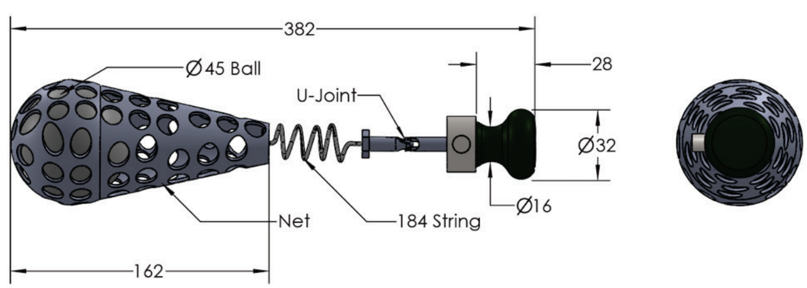
METRIC	UMTRI			TITLE: Car		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM	MODEL: A.L.	DRAWN: A.L.	PART NO:			
TOLERANCES	REV	INIT	DATE	MATERIAL: Wooden Toy Car*, Steel U-Joint, Plastic Knob, String		
	Initial Release	A.L.	2023/07/20	SCALE: 1:2	REV: 1	WEIGHT: 0.1 kg
*TOY Life Wooden Toy Car	1	A.L.	2023/08/03			SHEET 1 OF 1

Squishy

Squishy ball toy, 45 mm in diameter, constructed with 2 layers of balloons filled with cornstarch. Squishy ball was held in a nylon mesh pouch, 162 mm in length, attached by a string to a steel universal joint and uniaxial load cell.



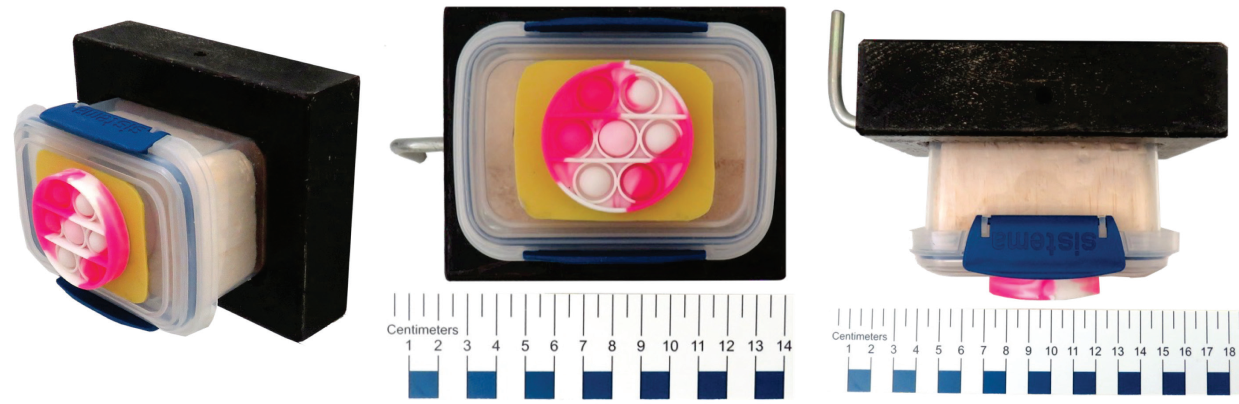




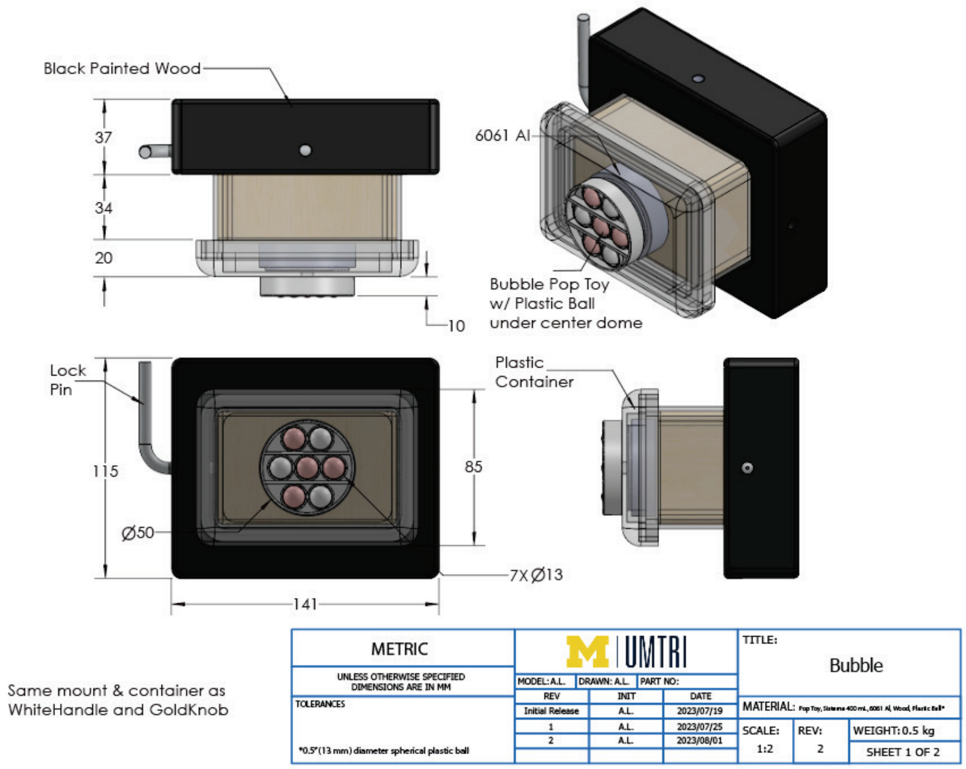
METRIC	UMTRI			TITLE: Squishy		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM	MODEL: A.L.	DRAWN: A.L.	PART NO:			
TOLERANCES	REV	INIT	DATE	MATERIAL: Squishy Ball*, Net, Steel U-Joint, Plastic Knob		
	Initial Release	A.L.	2023/07/21			
	1	A.L.	2023/08/03	SCALE:	REV:	WEIGHT: 0.1 kg
*Balloon filled with corn starch				1:2	1	SHEET 1 OF 1

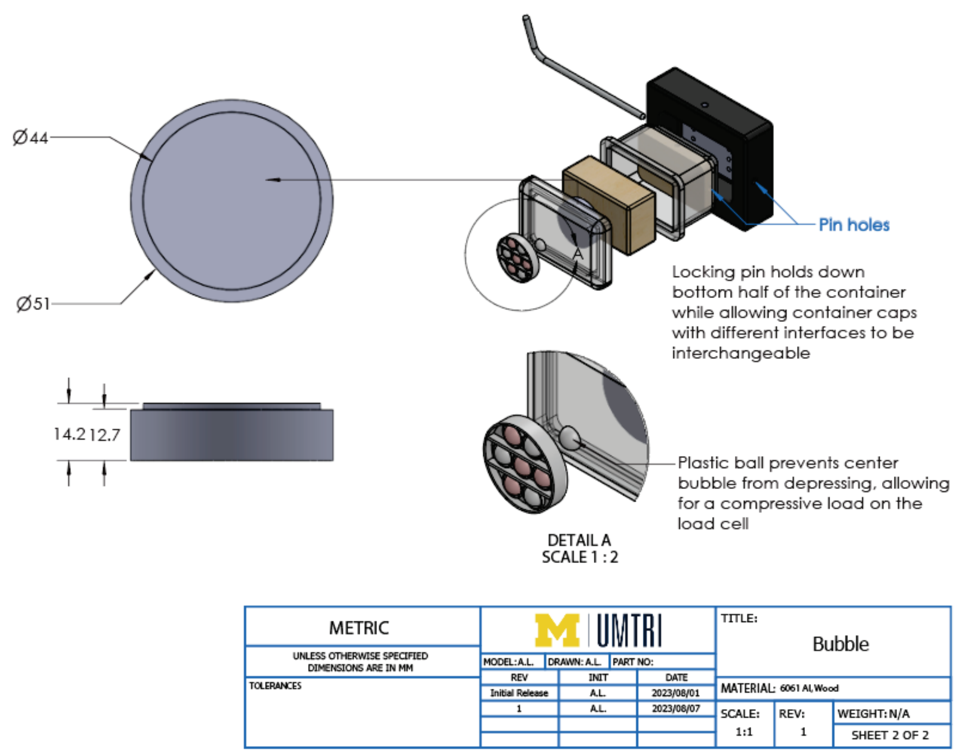
Bubble

Silicone bubble fidget, 50 mm in diameter with 7 individual bubble pop domes each 13 mm diameter and 9 mm of displacement travel, attached to a transparent plastic container that was locked to a mounting plate, attached to a six-axis load cell. A spherical plastic ball bearing (12 mm diameter) placed inside the center dome provided resistance to displacement and force application.



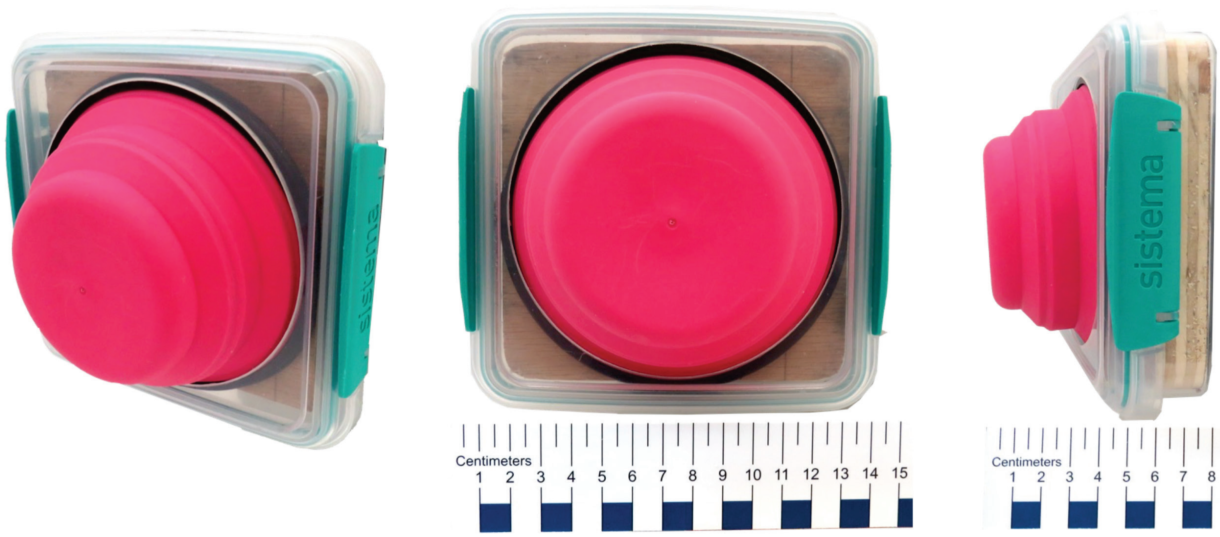
Oblique Front Top


Black Painted Wood
37
34
20
10
6061 Al
Bubble Pop Toy
w/ Plastic Ball
under center dome
Lock
Pin
115
Ø50
85
7X Ø13
141
Plastic
Container
Same mount & container as
WhiteHandle and GoldKnob
METRIC
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MM
TOLERANCES
*0.5"(13 mm) diameter spherical plastic ball
UMTRI
MODEL: A.L.
DRAWN: A.L.
PART NO:
REV
INIT
DATE
Initial Release
A.L.
2023/07/19
1
A.L.
2023/07/25
2
A.L.
2023/08/01
TITLE:
Bubble
MATERIAL: Pop Toy, Sistema 400 mL, 6061 Al, Wood, Plastic Ball*
SCALE: 1:2
REV: 2
WEIGHT: 0.5 kg
SHEET 1 OF 2

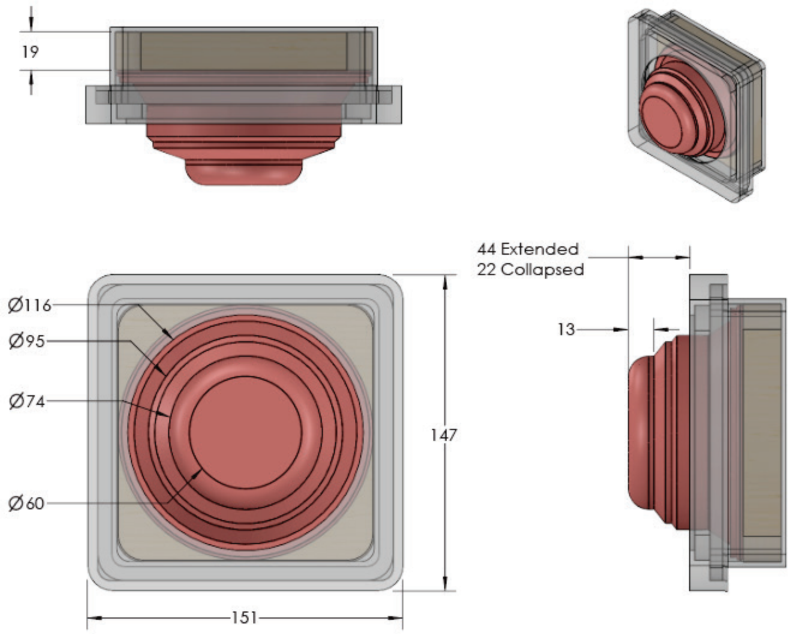

Ø44
Ø51
14.2
12.7
Pin holes
Locking pin holds down
bottom half of the container
while allowing container caps
with different interfaces to be
interchangeable
A
Plastic ball prevents center
bubble from depressing, allowing
for a compressive load on the
load cell
DETAIL A
SCALE 1 : 2
METRIC
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN MM
TOLERANCES
UMTRI
MODEL: A.L.
DRAWN: A.L.
PART NO:
REV
INIT
DATE
Initial Release
A.L.
2023/08/01
1
A.L.
2023/08/07
TITLE:
Bubble
MATERIAL: 6061 Al, Wood
SCALE: 1:1
REV: 1
WEIGHT: N/A
SHEET 2 OF 2

PushBowl

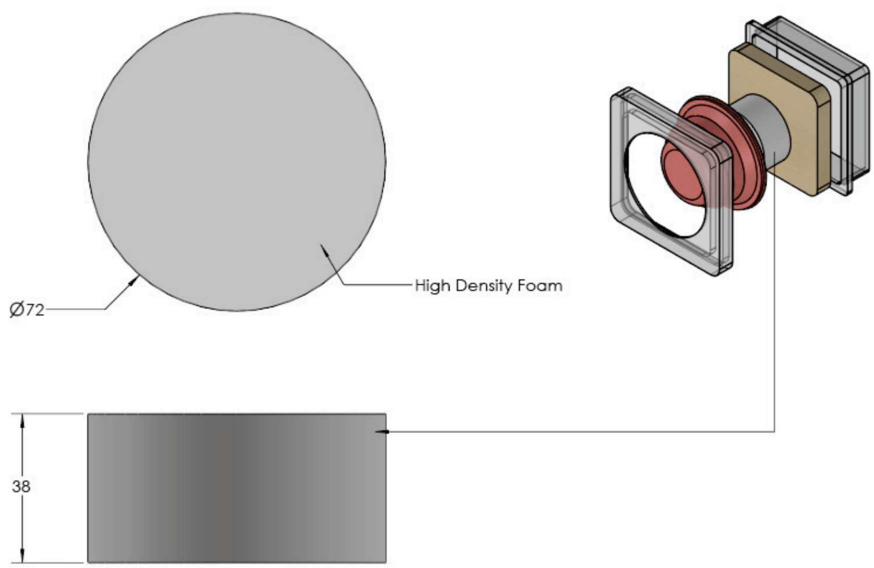
Silicone collapsible bowl, with an outer diameter of 116 mm, inner diameter of 74 mm, and 22 mm of collapsible depth, attached to a transparent plastic container that was locked to a mounting plate, attached to a six-axis load cell. A high-density foam cylinder, 72 mm in diameter, placed behind the silicone bowl provided resistance to force application.



Oblique Front Side



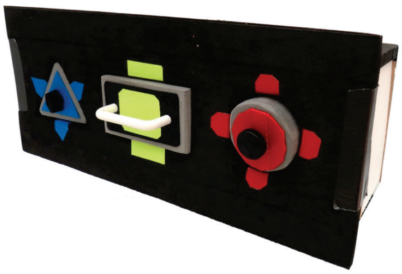
METRIC	MODEL: A.L.	DRAWN: A.L.	PART NO:	TITLE: Bowl		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM	REV	INIT	DATE	MATERIAL: Silicone Collapsable Bowl, Sistema Container, Wood		
TOLERANCES	Initial Release	A.L.	2023/07/19	SCALE:	REV:	WEIGHT: 0.2 kg
	1	A.L.	2023/08/01	1:2	1	SHEET 1 OF 2



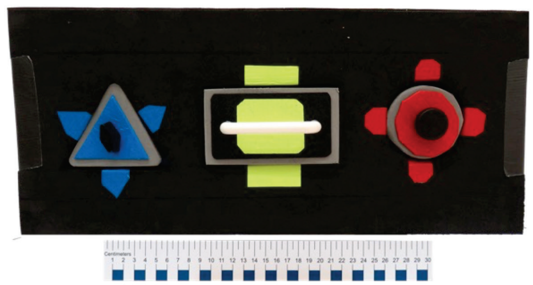
METRIC	MODEL: A.L.	DRAWN: A.L.	PART NO:	TITLE: Bowl (Foam)		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM	REV	INIT	DATE	MATERIAL: High Density Foam		
TOLERANCES	Initial Release	A.L.	2023/08/01	SCALE:	REV:	WEIGHT: 0.01 kg
				1:2	0	SHEET 2 OF 2

WhiteHandle_ShapeBoard

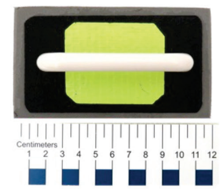
Cylindrical horizontal plastic drawer handle, 10 mm in diameter with an inner length of 66 mm for hand coupling and 22 mm finger clearance, mounted to high-density foam. Handle inserted into shape board constructed of plywood and foam and attached to a six-axis load cell. Foam prevented the white handle piece from inserting into the shape board and provided resistance to force application.



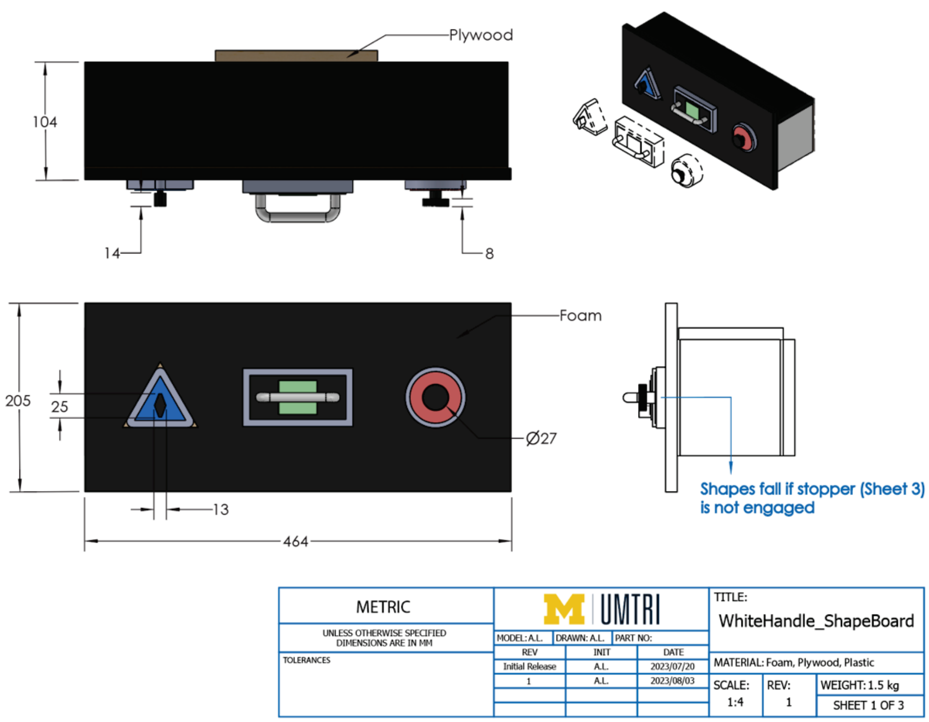
Oblique

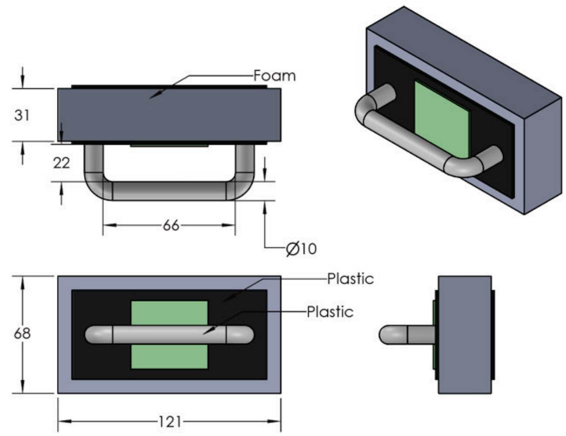


Front

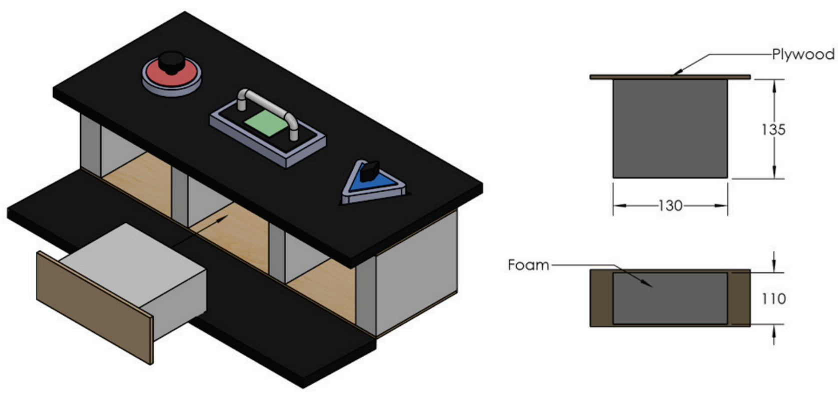


WhiteHandle Only





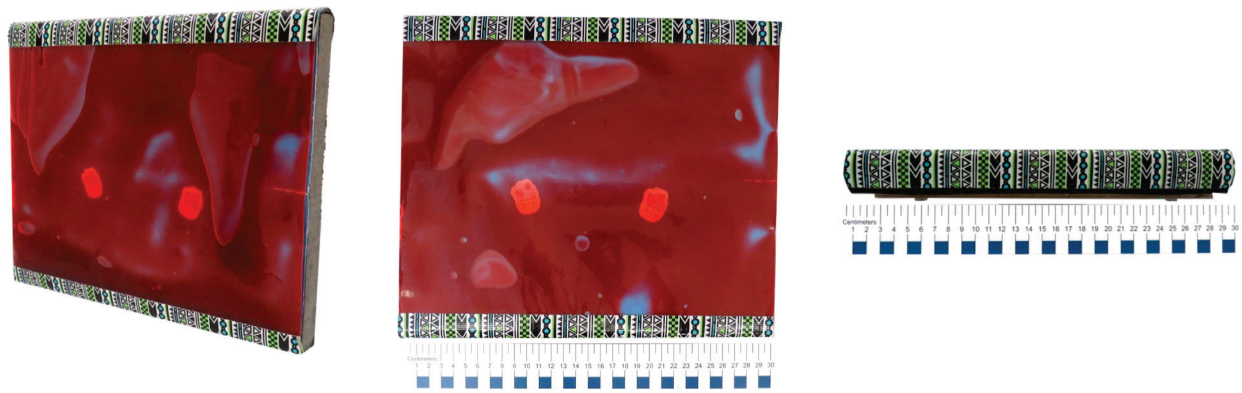
METRIC	UMTRI			TITLE: ShapeBoard (Rectangle)		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM	MODEL: A.L.	DRAWN: A.L.	PART NO:			
TOLERANCES	REV	INIT	DATE	MATERIAL: Foam, Plastic		
	Initial Release	A.L.	2023/08/03	SCALE: 1:2	REV: 0	WEIGHT: 0.04 kg
						SHEET 2 OF 3



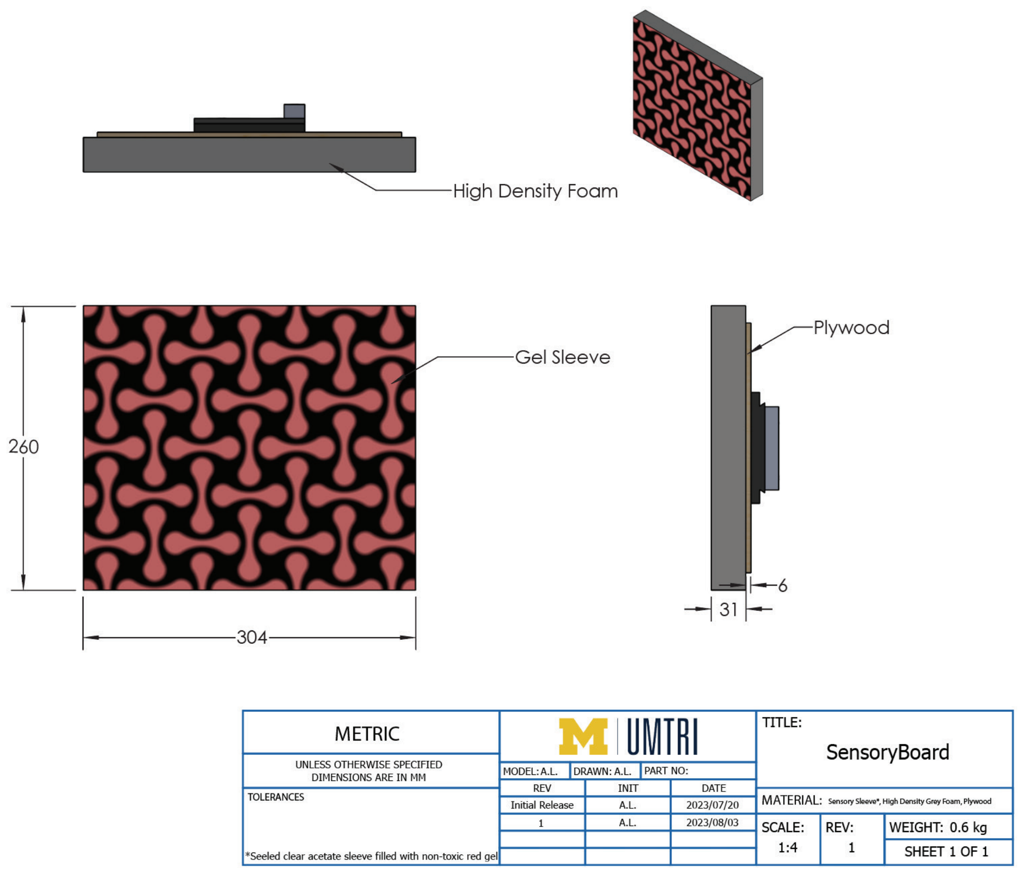
METRIC	UMTRI			TITLE: ShapeBoard (Stopper)		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM	MODEL: A.L.	DRAWN: A.L.	PART NO:			
TOLERANCES	REV	INIT	DATE	MATERIAL: High Density Foam, Plywood		
	Initial Release	A.L.	2023/08/03	SCALE: 1:4	REV: 0	WEIGHT: 0.1 kg
						SHEET 3 OF 3

SensoryBoard

A planar gel filled sensory tile (304 mm by 260 mm), mounted on plywood and attached to a six-axis load cell. Non-toxic colorful gel moved with force application.

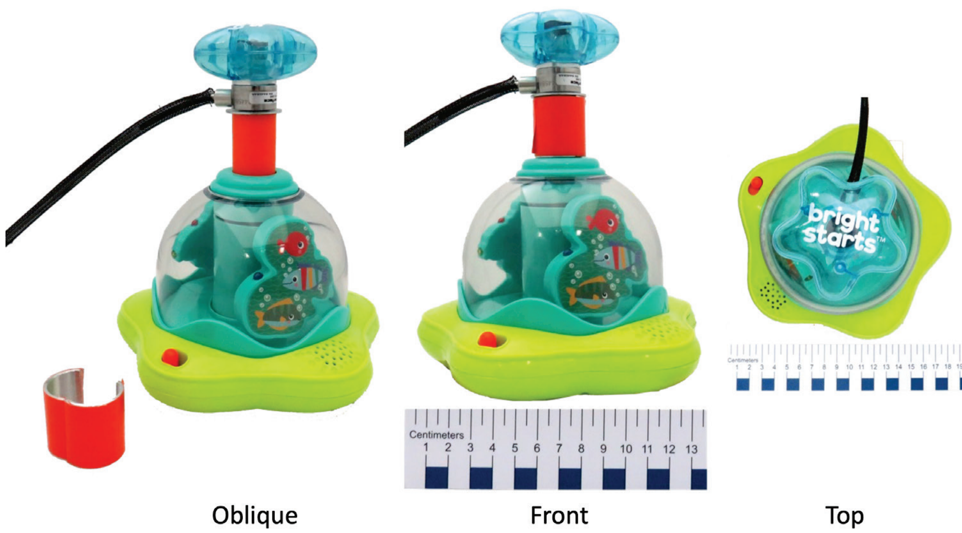


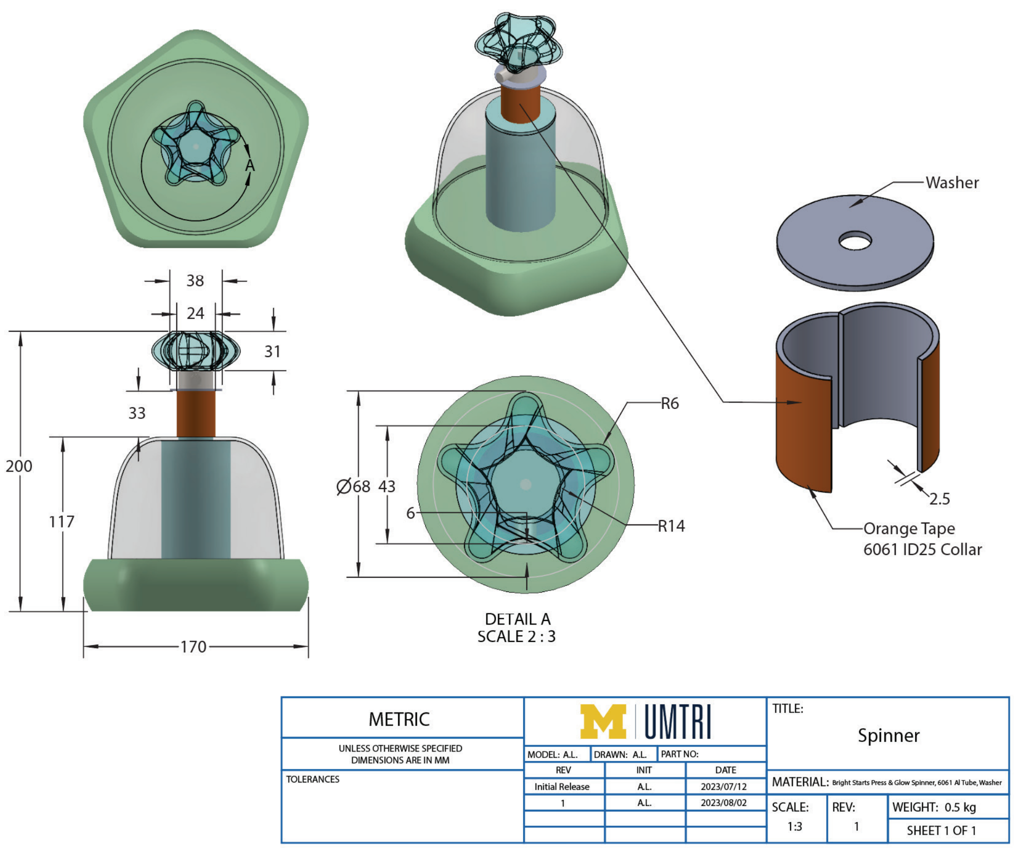
Oblique Front Top



Spinner

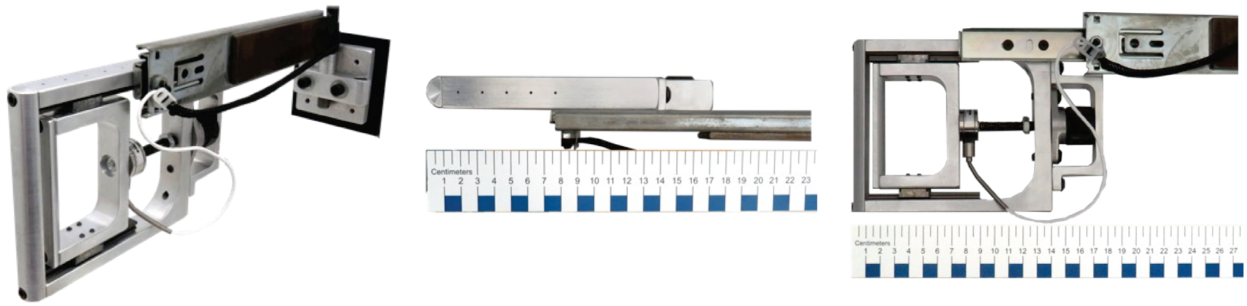
Spinner toy with fluted pentagon radiused knob with 25 mm radii and 68 mm outer diameter. A uniaxial load cell was integrated in-line with the spinner plunger. Collar added to the plunger to provide resistance force application.



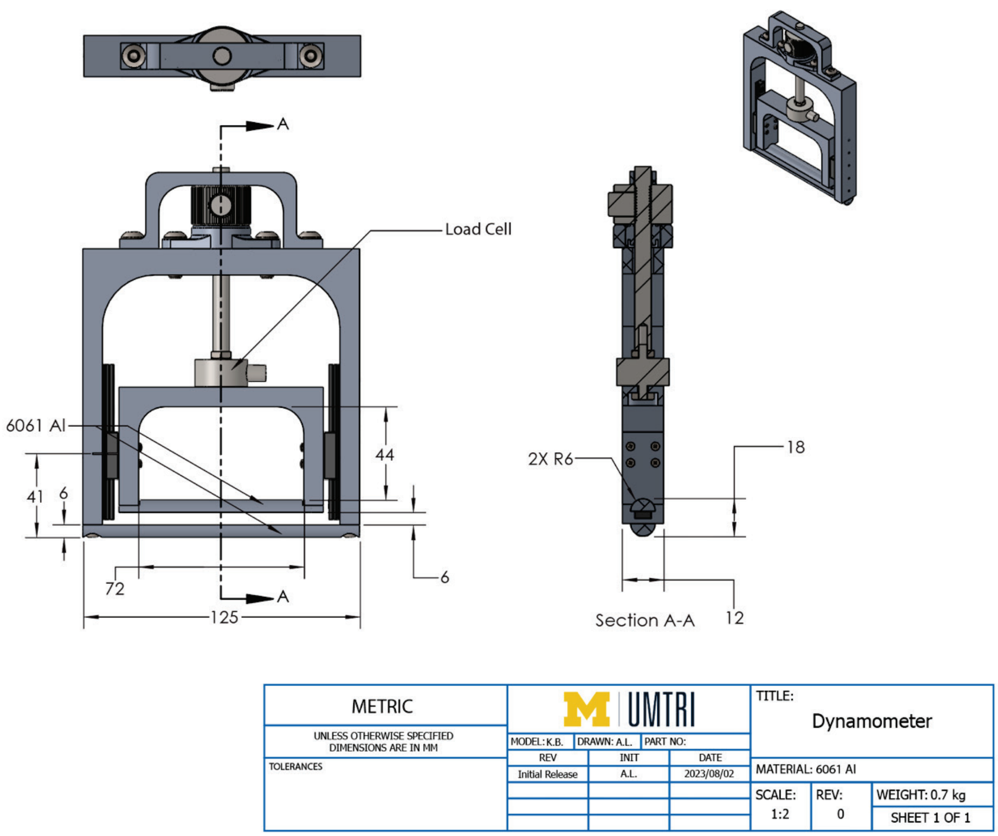


Dynamometer_24

Custom hand grip dynamometer with the aperture adjusted to 18 mm with 44 mm clearance. A uniaxial load cell was integrated within the fixture. The handle was fabricated with 6061 aluminum alloy. The dynamometer was held by investigators to support the instrument vertically and minimize the potential for application of horizontal force.

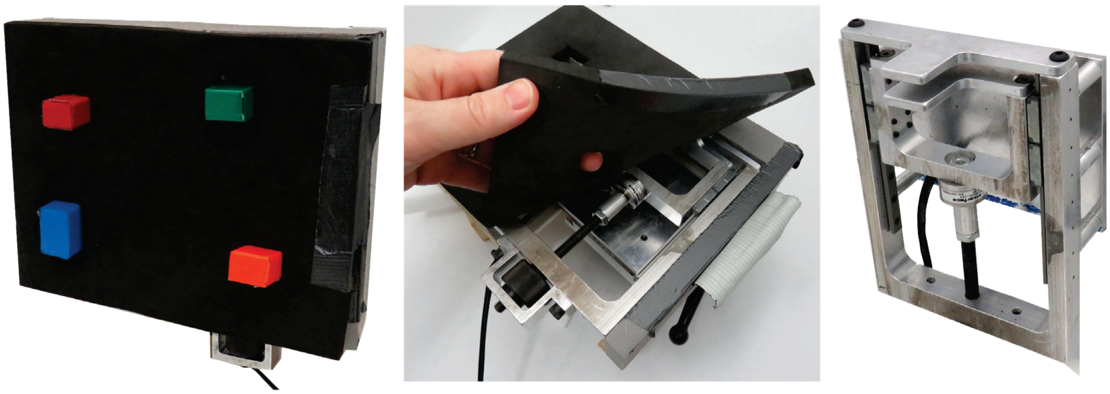


Oblique Top Side

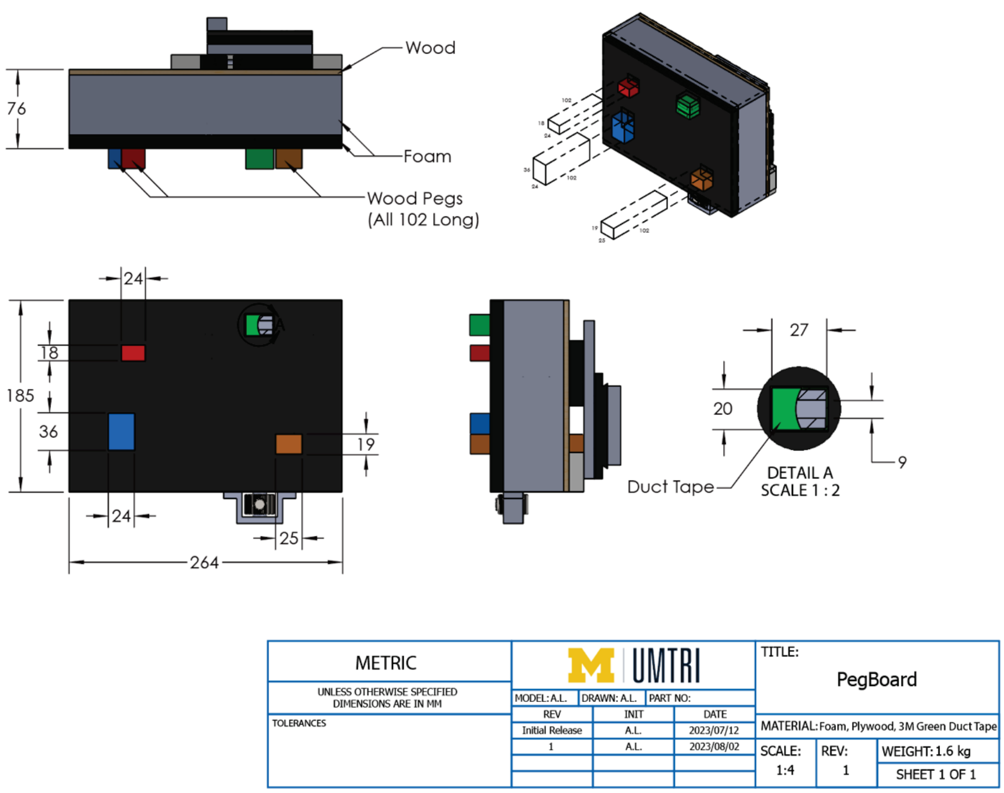


Pegboard

Custom pinch pull fixture with tab interface aperture adjusted to 20 mm. A uniaxial load was integrated within the fixture to measure pinch force and the fixture was attached to a six-axis load cell to measure the pull force. The handle was fabricated with 6061 aluminum alloy and covered in duct tape.

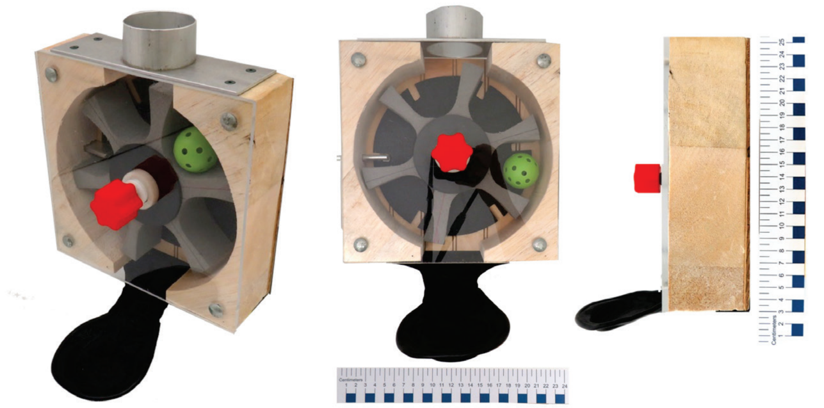


Oblique　　　Measurement　　　ISO: Pinch-Pull

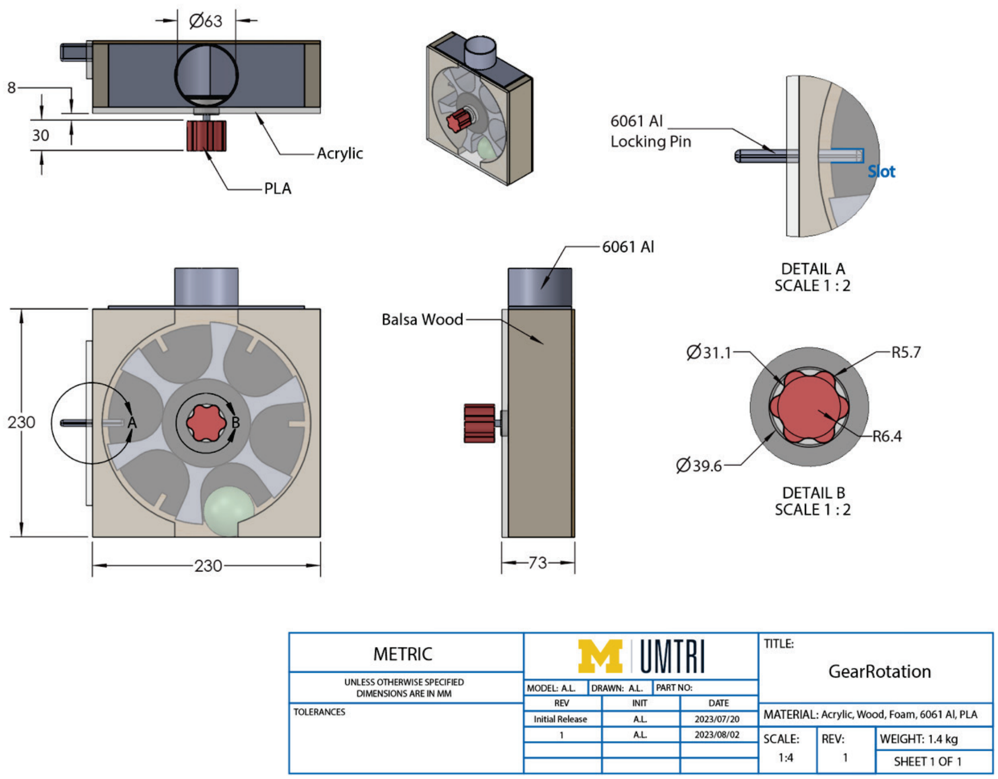


GearRotation

Fluted hexagon radiused knob with 8.5 mm radii, 39.6 mm outer diameter and 30 mm finger clearance, mounted to an acrylic plate and balsa wood box containing rotating spokes constructed from high-density foam, attached to a six-axis load cell. The turn knob was fabricated with 3D printed polylactic acid plastic (PLA). Locking pin prevented the spindles from rotating and provided resistance to a child's force application.

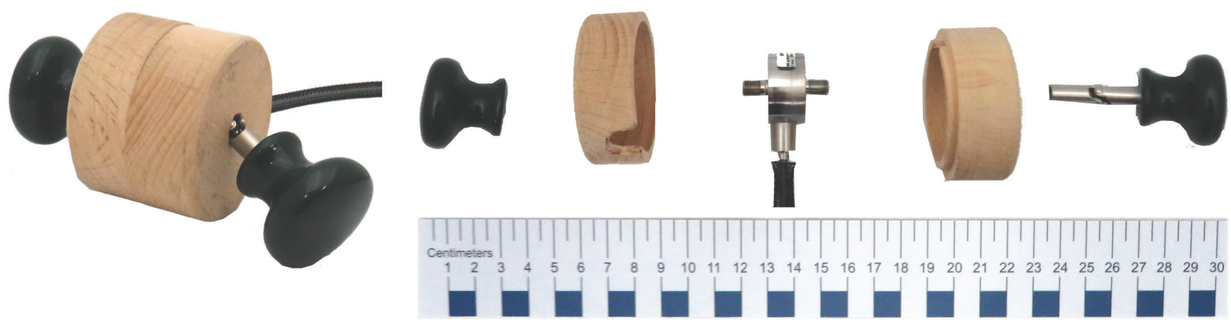


Oblique Front Side

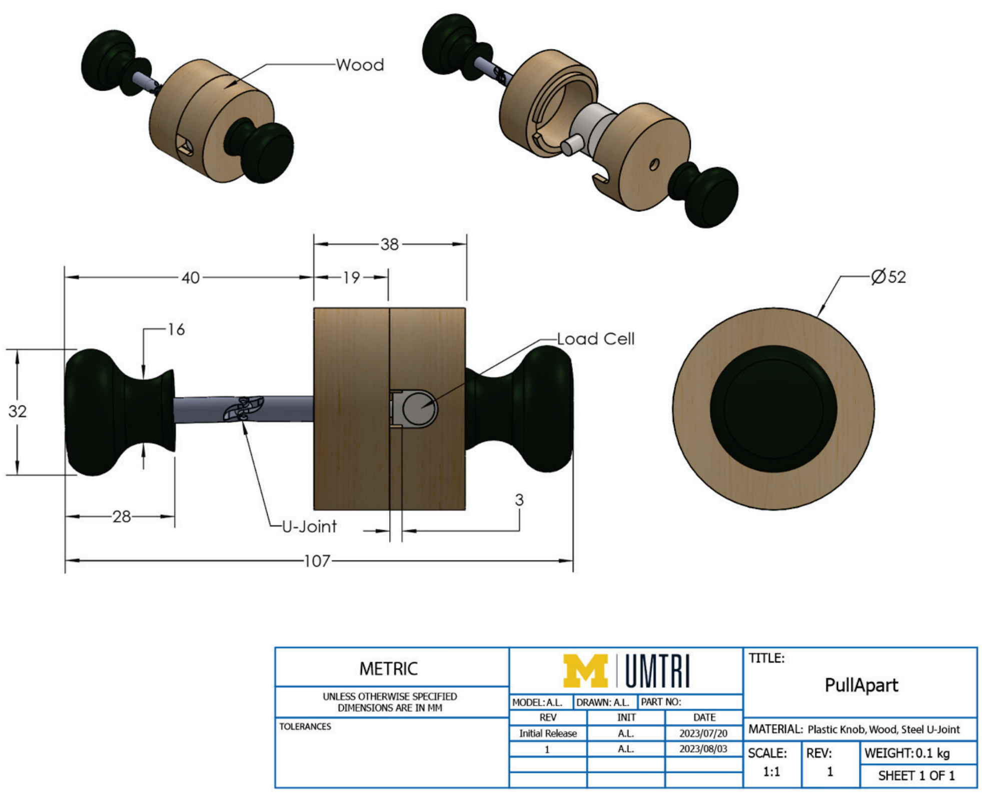


PullApart_32

Symmetric plastic knobs, with an outer diameter of 32 mm, inner diameter of 16 mm, and 28 mm finger clearance, asymmetrically mounted to a steel universal joint and wooden cylinder (52 mm in diameter). A uniaxial load cell was integrated with the universal joint, contained within the wooden cylinder, between the two plastic knobs. Total length of the pull apart fixture was 107 mm.

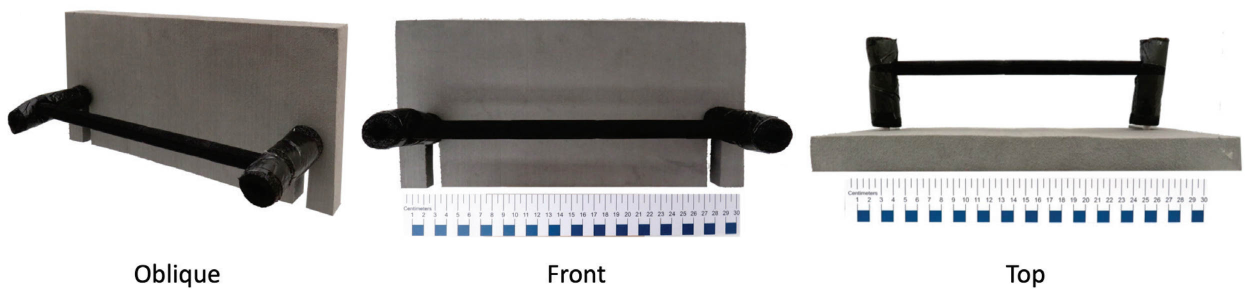


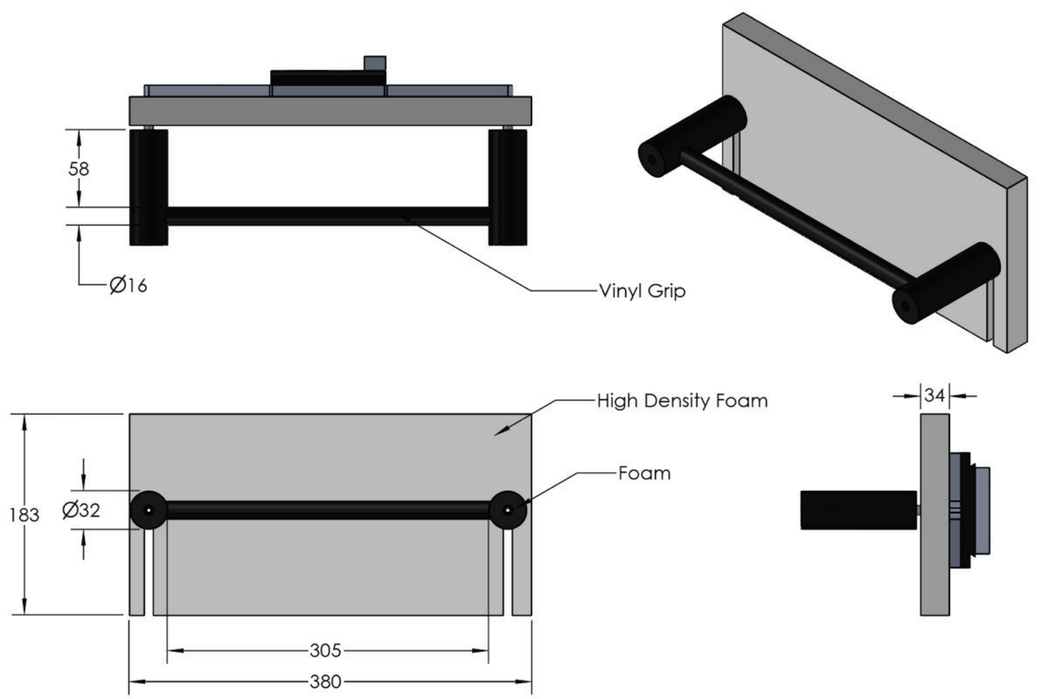
Oblique Front: Parsed



Bar

Cylindrical horizontal bar, 305 mm long, 16 mm in diameter and 58 mm clearance, attached to a six-axis load cell. The bar was coated in vinyl foam that provided a high-friction grip.



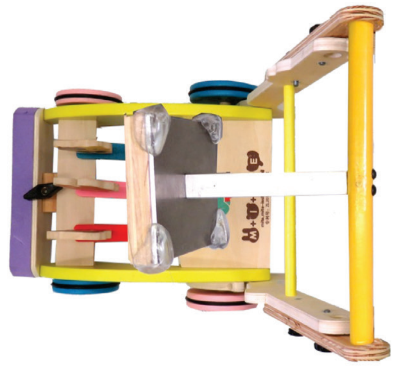


METRIC	UMTRI			TITLE: Bar		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM	MODEL: A.L.	DRAWN: A.L.	PART NO:			
TOLERANCES	REV	INIT	DATE	MATERIAL: 6061 Al, Vinyl Grip, Foam		
	Initial Release	A.L.	2023/07/12	SCALE: 1:4	REV: 1	WEIGHT: 1 kg
	1	A.L.	2023/08/02			SHEET 1 OF 1

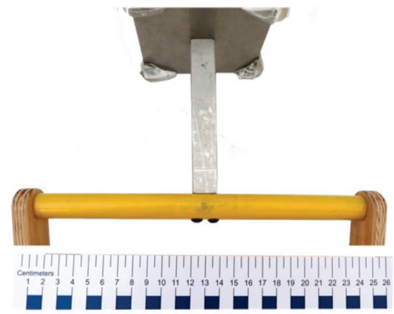
Cart

Cylindrical handle, 248 mm long and 20 mm in diameter, attached to a six-axis load cell. The handle was made of wood and painted with yellow spray paint.

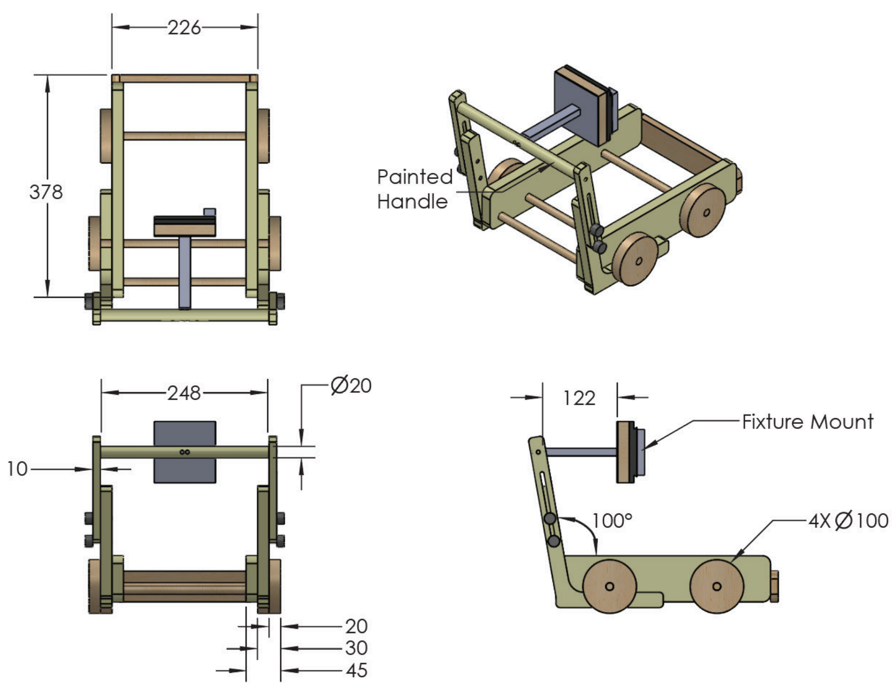
Oblique



Top



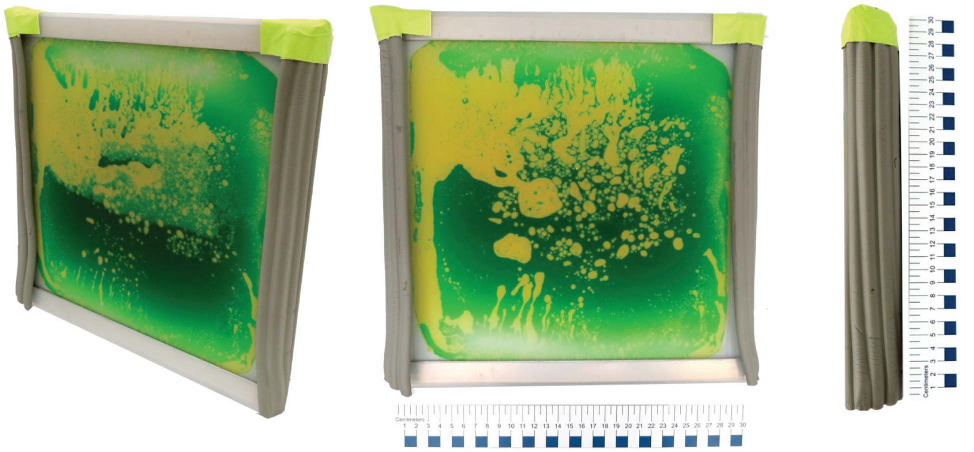
Handle



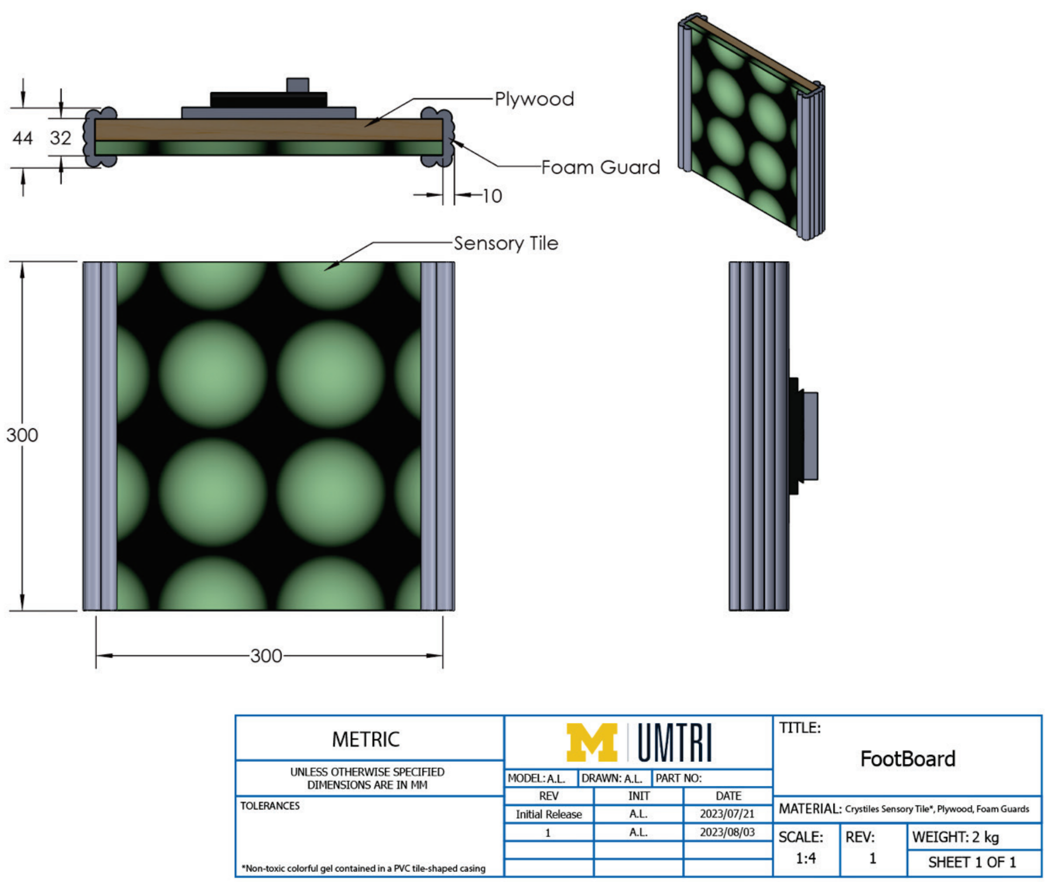
METRIC	UMTRI			TITLE: Cart		
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN MM	MODEL: A.L.	DRAWN: A.L.	PART NO:			
TOLERANCES	REV	INIT	DATE	MATERIAL: Wooden Toy Shopping Cart, Yellow Paint*		
	Initial Release	A.L.	2023/07/21			
	1	A.L.	2023/08/04	SCALE: 1:8	REV: 1	WEIGHT: 1.9 kg
*Krylon Fusion Gloss Sunbeam Spray Paint						SHEET 1 OF 1

FootBoard

A planar sensory tile (300 mm square), mounted on plywood and attached to a six-axis load cell. Non-toxic colorful gel moved with force application.



Oblique Front Side



APPENDIX C: Summary Statistics for Body Dimensions

This appendix contains tables of summary statistics for body dimensions of the participants. The body of the report describes the measurements.

Table C1
Stature (mm)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	683	44	630	635	678	749	772
6-8	0.50-0.74	F	7	648	16	632	633	642	672	674
6-8	0.50-0.74	Both	17	667	37	630	631	660	725	772
9-11	0.75-0.99	M	12	720	31	671	674	721	761	769
9-11	0.75-0.99	F	11	705	51	628	636	706	777	798
9-11	0.75-0.99	Both	23	713	41	628	645	716	769	798
12-17	1.00-1.49	M	39	764	37	672	716	760	813	852
12-17	1.00-1.49	F	24	734	44	640	675	730	806	809
12-17	1.00-1.49	Both	63	752	42	640	676	755	810	852
18-23	1.50-1.99	M	32	836	43	743	772	834	904	927
18-23	1.50-1.99	F	36	811	38	730	747	808	871	902
18-23	1.50-1.99	Both	68	822	42	730	755	820	899	927

Table C2
Body Weight (kg)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	9.2	1.2	7.8	7.9	8.9	11.0	11.8
6-8	0.50-0.74	F	7	7.5	0.5	6.7	6.9	7.6	8.1	8.2
6-8	0.50-0.74	Both	17	8.5	1.3	6.7	7.2	8.2	10.4	11.8
9-11	0.75-0.99	M	12	9.7	1.1	8.4	8.6	9.3	11.5	11.6
9-11	0.75-0.99	F	11	9.4	1.7	8.0	8.1	8.9	12.7	12.8
9-11	0.75-0.99	Both	23	9.5	1.4	8.0	8.2	9.0	12.4	12.8
12-17	1.00-1.49	M	39	10.5	1.3	8.6	8.7	10.1	12.6	13.8
12-17	1.00-1.49	F	24	9.8	1.4	7.5	7.6	9.8	11.7	12.9
12-17	1.00-1.49	Both	63	10.2	1.3	7.5	8.1	10.1	12.6	13.8
18-23	1.50-1.99	M	32	12.8	1.4	9.6	10.4	12.7	15.1	16.4
18-23	1.50-1.99	F	36	11.2	1.4	8.9	9.2	11.1	13.4	14.4
18-23	1.50-1.99	Both	68	12.0	1.6	8.9	9.4	12.2	14.4	16.4

Table C3
BMI (kg/m^2)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	20.4	3.1	16.8	17.2	19.6	25.0	25.4
6-8	0.50-0.74	F	7	17.9	1.8	14.8	15.3	18.4	19.7	20.0
6-8	0.50-0.74	Both	17	19.3	2.8	14.8	15.9	18.8	24.5	25.4
9-11	0.75-0.99	M	12	18.9	1.9	15.4	16.3	19.1	21.8	22.0
9-11	0.75-0.99	F	11	19.2	3.2	12.9	15.1	18.8	23.7	24.5
9-11	0.75-0.99	Both	23	19.1	2.5	12.9	15.4	19.1	22.8	24.5
12-17	1.00-1.49	M	39	18.0	1.2	15.5	16.1	18.0	19.4	20.8
12-17	1.00-1.49	F	24	18.0	1.4	15.5	15.8	17.8	19.9	21.0
12-17	1.00-1.49	Both	63	18.0	1.3	15.5	15.7	18.0	19.8	21.0
18-23	1.50-1.99	M	32	18.3	1.4	15.5	15.6	18.6	20.2	20.5
18-23	1.50-1.99	F	36	17.0	1.6	14.0	14.5	16.9	20.3	21.3
18-23	1.50-1.99	Both	68	17.6	1.6	14.0	15.4	17.5	20.4	21.3

Table C4
Erect Sitting Height (mm)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	430	18	400	402	428	454	455
6-8	0.50-0.74	F	7	407	22	374	377	404	430	430
6-8	0.50-0.74	Both	17	420	22	374	383	426	453	455
9-11	0.75-0.99	M	12	440	14	413	418	440	459	462
9-11	0.75-0.99	F	11	440	25	396	400	445	474	475
9-11	0.75-0.99	Both	23	440	20	396	404	442	472	475
12-17	1.00-1.49	M	39	468	21	423	432	466	494	516
12-17	1.00-1.49	F	24	458	25	415	426	452	488	528
12-17	1.00-1.49	Both	63	464	23	415	428	463	494	528
18-23	1.50-1.99	M	32	504	22	462	471	508	538	541
18-23	1.50-1.99	F	36	486	23	434	447	485	521	525
18-23	1.50-1.99	Both	68	494	24	434	462	494	531	541

Table C5
Seated Acromion Height (mm)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	280	9	260	264	282	289	290
6-8	0.50-0.74	F	7	259	27	235	237	245	299	311
6-8	0.50-0.74	Both	17	271	21	235	240	279	294	311
9-11	0.75-0.99	M	12	277	11	264	265	276	292	300
9-11	0.75-0.99	F	11	279	15	251	256	281	300	302
9-11	0.75-0.99	Both	23	278	13	251	261	281	300	302
12-17	1.00-1.49	M	39	299	17	258	272	299	320	337
12-17	1.00-1.49	F	24	295	18	266	274	297	322	325
12-17	1.00-1.49	Both	63	298	17	258	272	298	322	337
18-23	1.50-1.99	M	32	321	24	265	286	322	350	385
18-23	1.50-1.99	F	36	306	21	262	266	307	338	341
18-23	1.50-1.99	Both	68	314	24	262	267	315	346	385

Table C6
Maximum Reach (mm)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	296	20	269	273	297	322	328
6-8	0.50-0.74	F	7	308	28	279	281	308	337	339
6-8	0.50-0.74	Both	17	301	23	269	274	297	334	339
9-11	0.75-0.99	M	12	305	39	260	264	291	360	363
9-11	0.75-0.99	F	11	296	33	261	264	292	334	339
9-11	0.75-0.99	Both	23	302	36	260	261	291	359	363
12-17	1.00-1.49	M	39	338	26	288	295	336	374	393
12-17	1.00-1.49	F	24	330	31	270	276	334	372	390
12-17	1.00-1.49	Both	63	335	28	270	286	335	379	393
18-23	1.50-1.99	M	32	341	31	303	309	332	394	399
18-23	1.50-1.99	F	36	341	37	286	292	335	385	458
18-23	1.50-1.99	Both	68	341	34	286	301	332	394	458

APPENDIX D: Summary Statistics for Force Exertion

This appendix contains tables of summary statistics for force exertion across the 23 task conditions listed in the body of the report. Within each trial, the highest value of a 0.5-second moving average of the on-axis force was computed. The largest value across the trials in each condition for each subject was used to compute the statistics in this appendix. The N values in each table reflect the number of subjects for whom valid data were available.

Note that the child photos in this appendix were staged with a child for whom we obtained a photo release. These photos were not taken during data collection. The environment was modified to improve the clarity of the photos, including by using a backdrop. During data collection two investigators and the child's caregiver were always present.

The scatter plots include an approximating curve for each gender created by local polynomial regression fitting (also known as local estimation smoothing, or loess). The curve is constructed by generating an approximating point at each value of the independent variable. Each of these points on the curve is created by fitting a quadratic function to the points near the desired point, weighting points closer to the point of interest higher than those farther away. The complete curve is obtained by a line passing through these individual points. The algorithm uses the geom_smooth() function in the ggplot2 library in R version 4.3.2, which is based on the loess() function in R. Default values for loess() were used, which include quadratic local fitting. When a plot has relatively few data points, and at the ends, the curve is a less reliable approximation of the trend in the data. These curves are intended to show qualitative trends and should not be taken as representing the true mean value at any point in the curve.

The box plots were created using the geom_boxplot() function using the ggplot2 library in R 4.3.2. Boxplots are a non-parametric way to represent the distribution of a dataset. The line across the center of the box shows the median value within the group. The lower and upper ends of the box correspond to the first and third quartiles (the 25th and 75th percentiles), i.e., the interquartile range (IQR). The upper whisker (line) extends from the box to the largest value no further than 1.5 * IQR from the box. The lower whisker extends from the box to the smallest value at most 1.5 * IQR of the box. Data beyond the end of the whiskers are called "outlying" points and are plotted individually.

The tables contain the number of observations, mean, standard deviation, and quantile values for the outcome measure, which was the maximum value of a 0.5-second moving average within the time window identified for the trial during data processing.

BarHandle_Pull

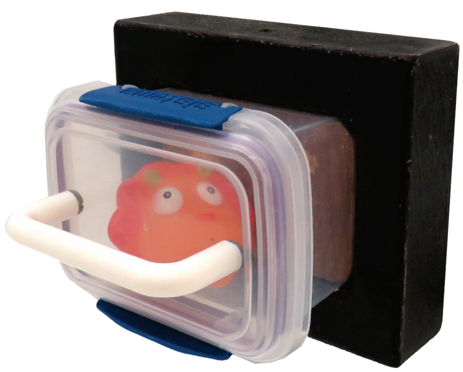
Description: Standing or Seated

Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

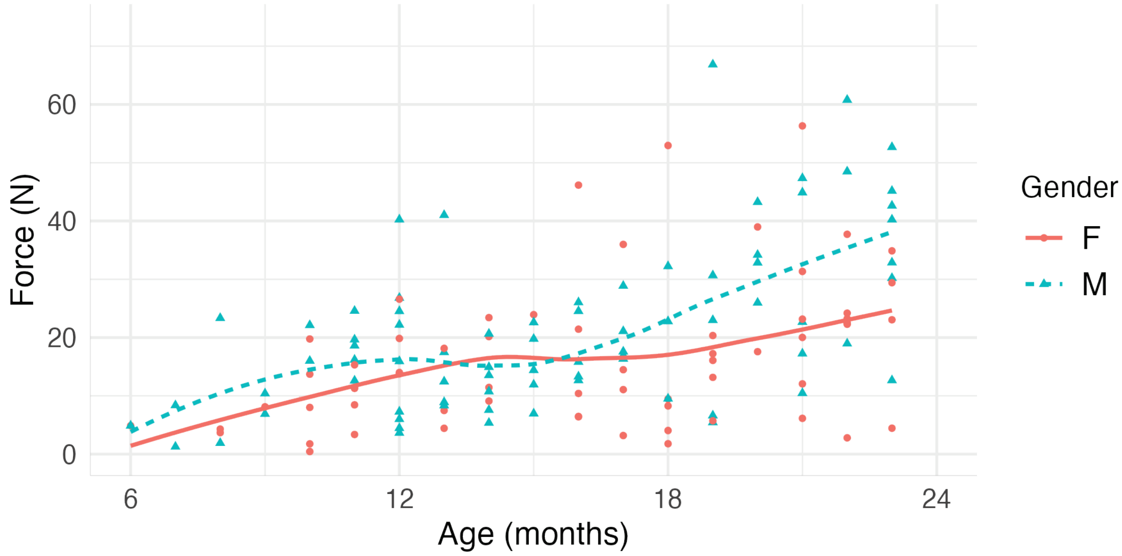
Posture: Pull with one or two hands

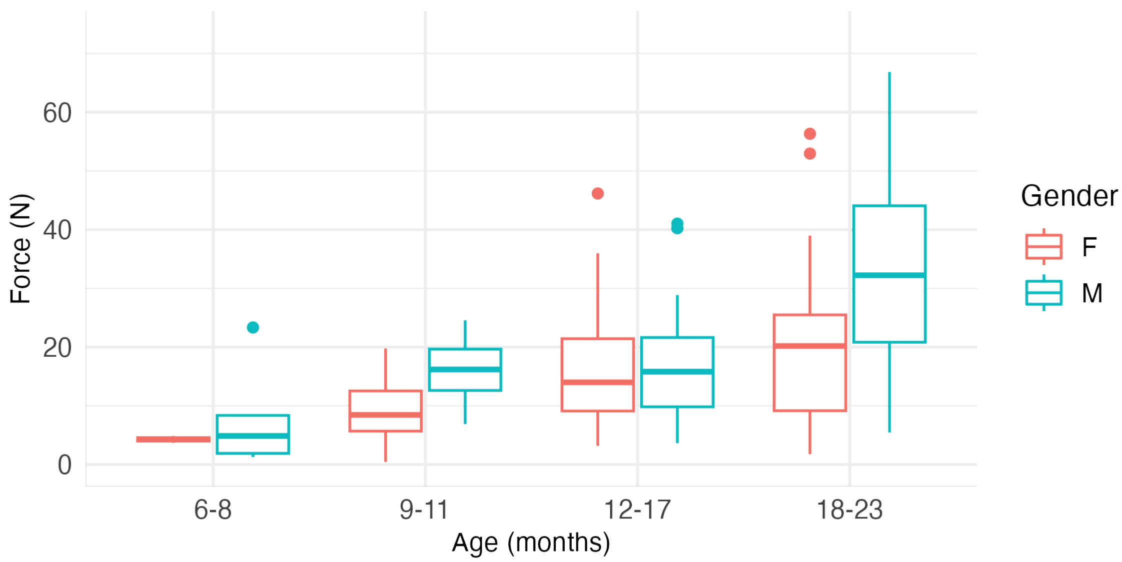
Interface: WhiteHandle

Units: Newton



BarHandle_Pull





BarHandle_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	5	8.0	9.1	1.3	1.4	4.9	20.4	23.3
6-8	0.50-0.74	F	3	4.3	0.6	3.7	3.8	4.3	4.8	4.9
6-8	0.50-0.74	Both	8	6.6	7.1	1.3	1.5	4.6	18.1	23.3
9-11	0.75-0.99	M	9	16.3	5.7	6.9	8.3	16.2	23.6	24.6
9-11	0.75-0.99	F	11	9.2	5.9	0.5	1.1	8.5	17.5	19.8
9-11	0.75-0.99	Both	20	12.4	6.7	0.5	1.7	12.0	22.3	24.6
12-17	1.00-1.49	M	35	16.6	9.1	3.7	5.1	15.8	32.3	41.0
12-17	1.00-1.49	F	21	16.6	10.7	3.2	4.4	14.0	36.0	46.2
12-17	1.00-1.49	Both	56	16.6	9.6	3.2	4.5	14.7	37.1	46.2
18-23	1.50-1.99	M	27	31.9	16.4	5.5	7.5	32.2	58.3	66.8
18-23	1.50-1.99	F	28	20.7	14.2	1.8	3.2	20.2	48.1	56.3
18-23	1.50-1.99	Both	55	26.2	16.2	1.8	4.3	23.1	54.0	66.8

GoldKnob_Pull

Description: Standing or Seated

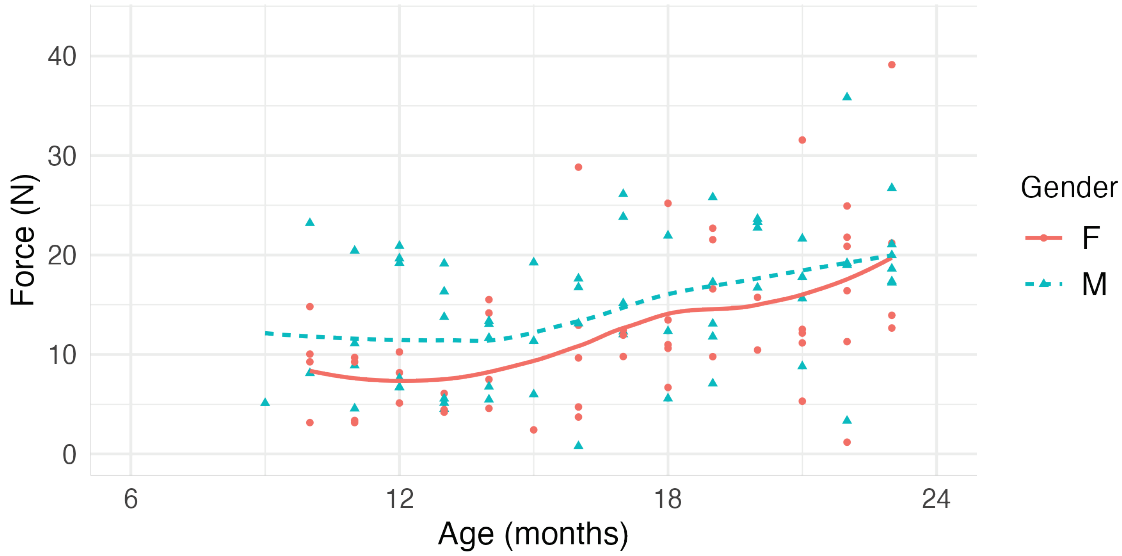
Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

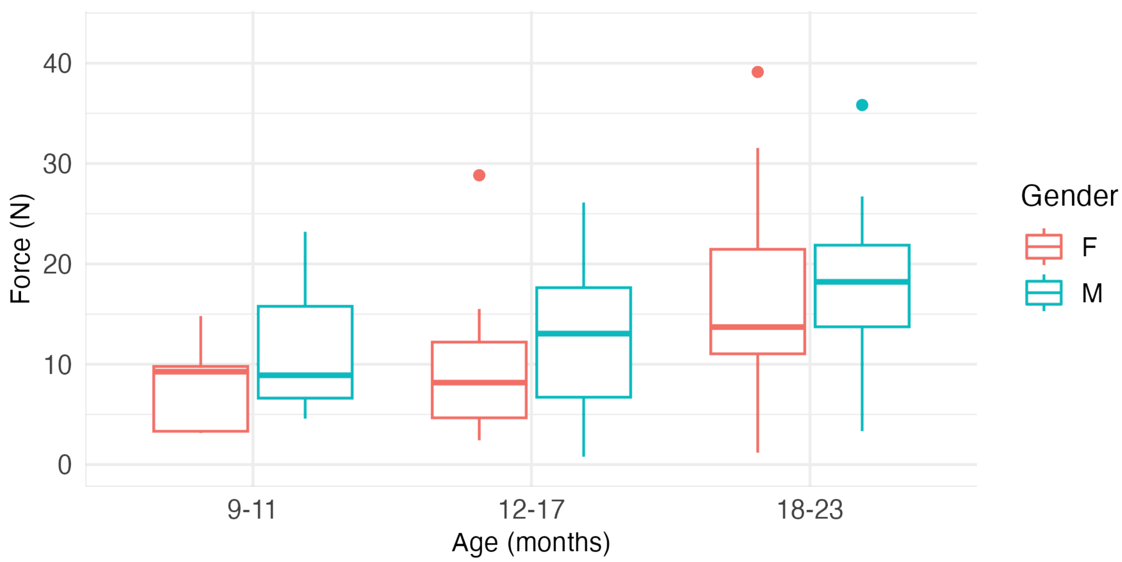
Posture: Pull with one or two hands

Interface: GoldKnob

Units: Newton

GoldKnob_Pull





GoldKnob_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	0							
6-8	0.50-0.74	F	0							
6-8	0.50-0.74	Both	0							
9-11	0.75-0.99	M	7	11.6	7.3	4.6	4.7	8.9	22.4	23.2
9-11	0.75-0.99	F	8	7.8	4.2	3.2	3.2	9.3	13.1	14.8
9-11	0.75-0.99	Both	15	9.6	6.0	3.2	3.2	9.3	21.3	23.2
12-17	1.00-1.49	M	29	12.8	6.4	0.8	4.8	13.1	22.7	26.1
12-17	1.00-1.49	F	19	9.3	6.1	2.4	3.6	8.2	16.9	28.8
12-17	1.00-1.49	Both	48	11.4	6.5	0.8	3.9	11.5	22.8	28.8
18-23	1.50-1.99	M	26	17.8	7.1	3.3	6.0	18.2	26.5	35.8
18-23	1.50-1.99	F	26	16.2	8.3	1.2	5.7	13.7	30.0	39.1
18-23	1.50-1.99	Both	52	17.0	7.7	1.2	5.5	17.0	28.9	39.1

TissueBox_Pull

Description: Standing or Seated

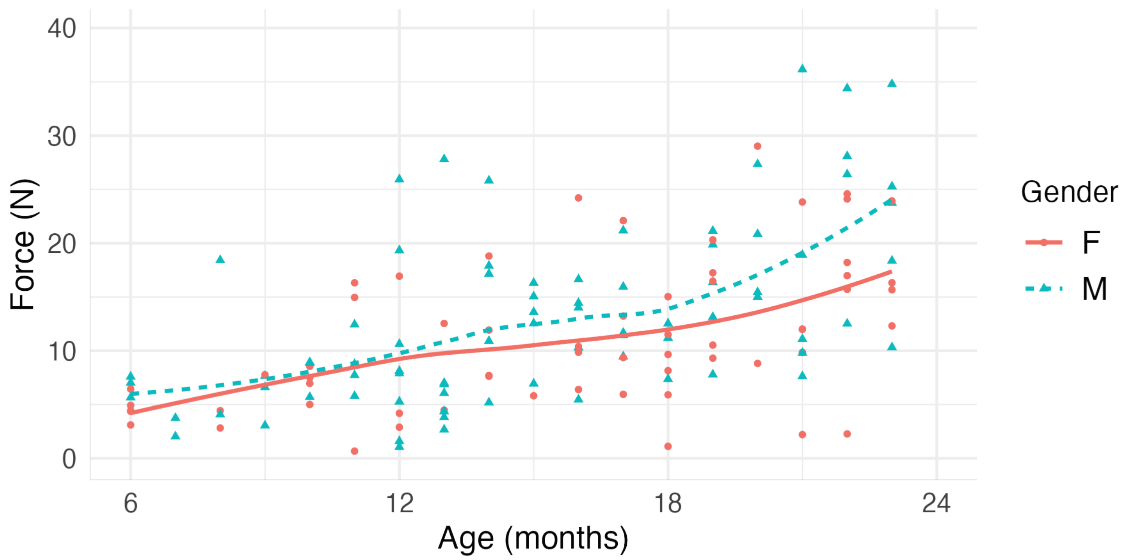
Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

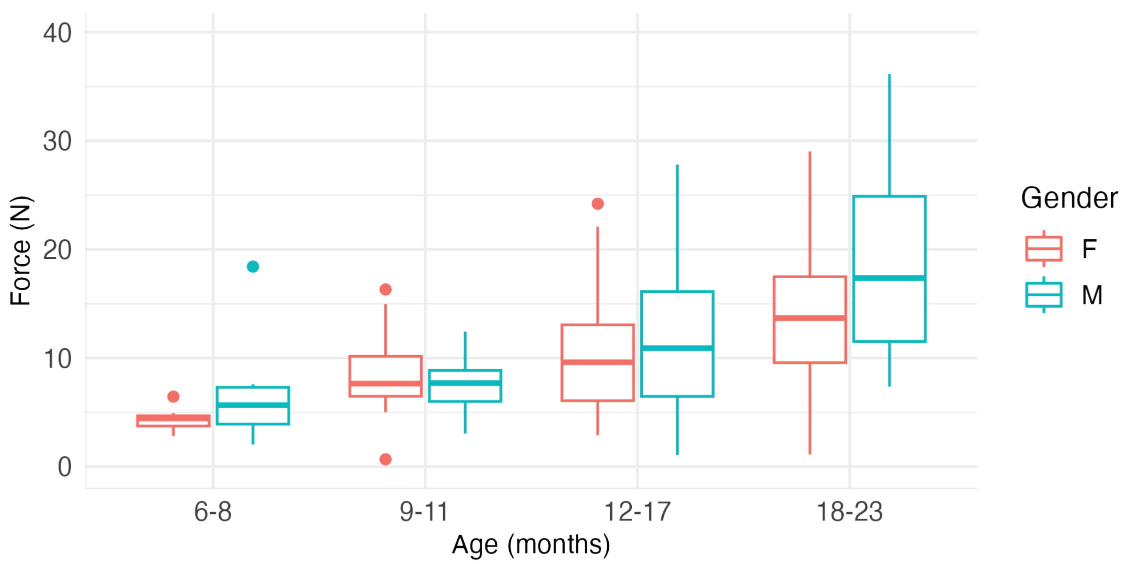
Posture: Pull with one or two hands

Interface: TissueBox

Units: Newton

TissueBox_Pull





TissueBox_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	7	6.9	5.4	2.0	2.5	5.7	15.2	18.4
6-8	0.50-0.74	F	7	4.4	1.2	2.8	2.9	4.4	6.0	6.4
6-8	0.50-0.74	Both	14	5.6	4.0	2.0	2.5	4.4	11.4	18.4
9-11	0.75-0.99	M	10	7.6	2.5	3.1	4.2	7.7	10.9	12.4
9-11	0.75-0.99	F	8	8.5	5.1	0.7	2.2	7.6	15.8	16.3
9-11	0.75-0.99	Both	18	8.0	3.8	0.7	2.7	7.7	15.2	16.3
12-17	1.00-1.49	M	35	11.7	6.9	1.1	2.3	10.9	25.8	27.8
12-17	1.00-1.49	F	18	10.8	6.2	2.9	4.0	9.6	22.4	24.2
12-17	1.00-1.49	Both	53	11.4	6.7	1.1	2.8	10.4	24.9	27.8
18-23	1.50-1.99	M	26	18.7	8.7	7.4	7.7	17.4	34.7	36.2
18-23	1.50-1.99	F	28	14.0	7.2	1.1	2.2	13.7	24.4	29.0
18-23	1.50-1.99	Both	54	16.3	8.2	1.1	4.6	15.6	30.9	36.2

Car_ToW_Pull

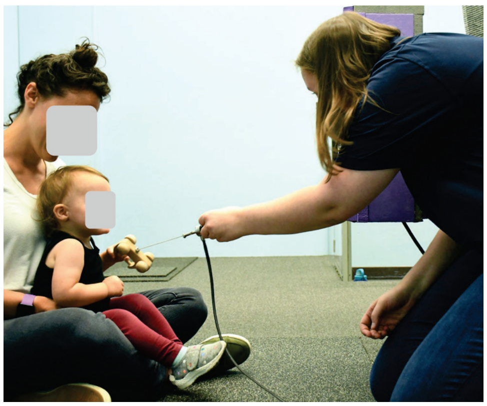
Description: Standing or Seated

Configuration: Stand, Lap, Booster, or Floor

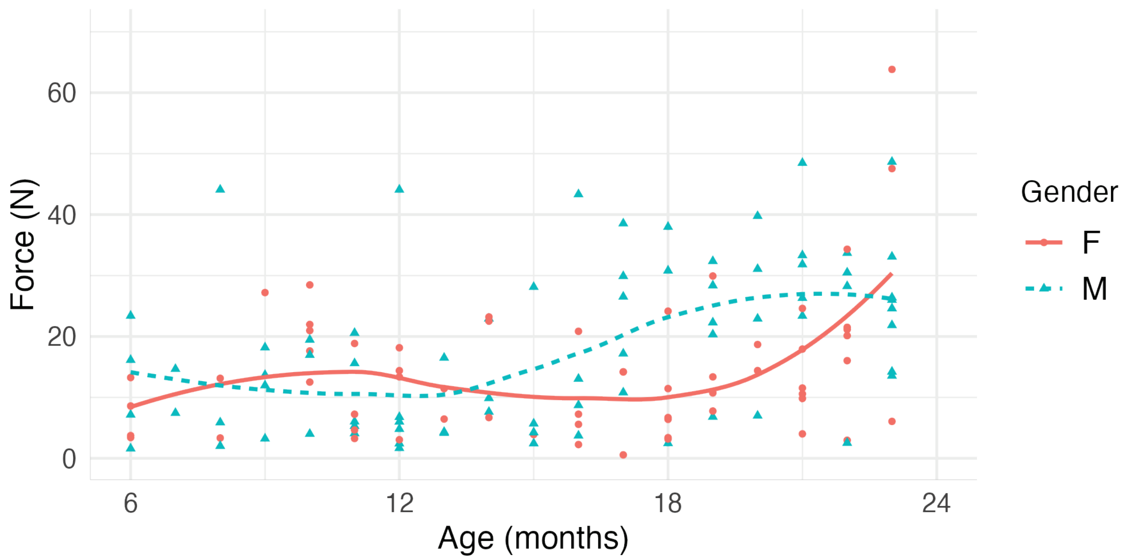
Posture: Pull with one or two hands

Interface: Car

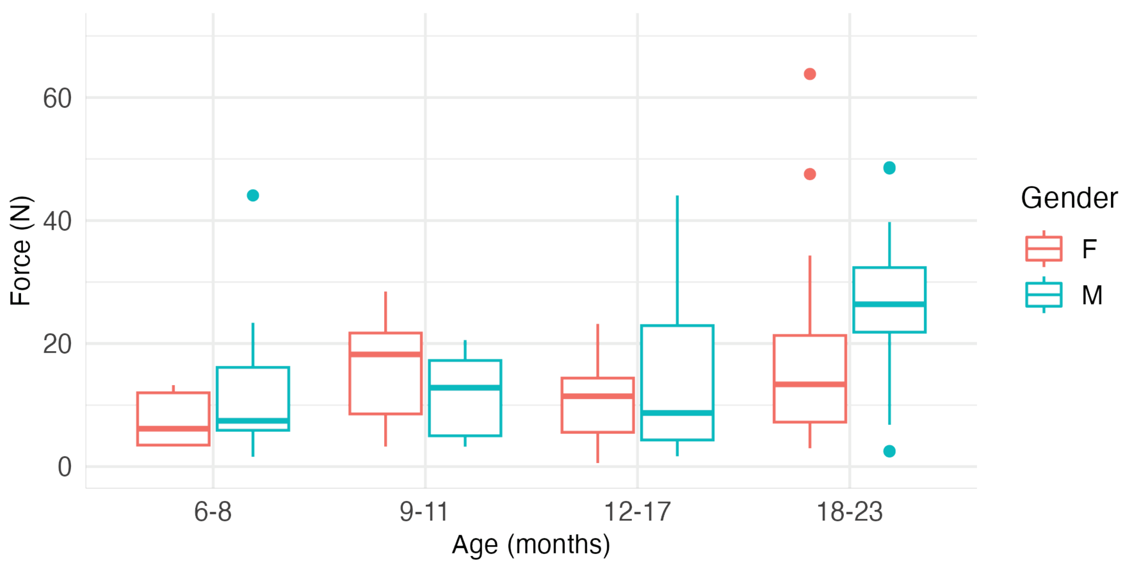
Units: Newton



Car_ToW_Pull



Force (N)
0
20
40
60
6
12
18
24
Age (months)
Gender
F
M



Force (N)
0
20
40
60
6-8
9-11
12-17
18-23
Age (months)
Gender
F
M

Car_ToW_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	9	13.6	13.5	1.6	1.8	7.4	35.8	44.1
6-8	0.50-0.74	F	6	7.6	4.8	3.3	3.4	6.2	13.2	13.3
6-8	0.50-0.74	Both	15	11.2	11.0	1.6	1.9	7.4	29.6	44.1
9-11	0.75-0.99	M	12	11.6	6.7	3.2	3.7	12.8	20.0	20.6
9-11	0.75-0.99	F	10	16.3	9.0	3.3	3.9	18.2	27.9	28.5
9-11	0.75-0.99	Both	22	13.7	8.0	3.2	3.3	14.6	26.9	28.5
12-17	1.00-1.49	M	25	14.5	13.3	1.7	2.4	8.7	42.4	44.1
12-17	1.00-1.49	F	17	11.1	7.3	0.6	1.9	11.4	22.7	23.2
12-17	1.00-1.49	Both	42	13.1	11.3	0.6	2.3	9.3	38.1	44.1
18-23	1.50-1.99	M	29	25.8	11.8	2.5	4.2	26.4	45.0	48.7
18-23	1.50-1.99	F	27	17.1	14.0	3.0	3.2	13.4	43.6	63.8
18-23	1.50-1.99	Both	56	21.6	13.5	2.5	3.1	21.7	47.8	63.8

Squishy_ToW_Pull

Description: Standing or Seated

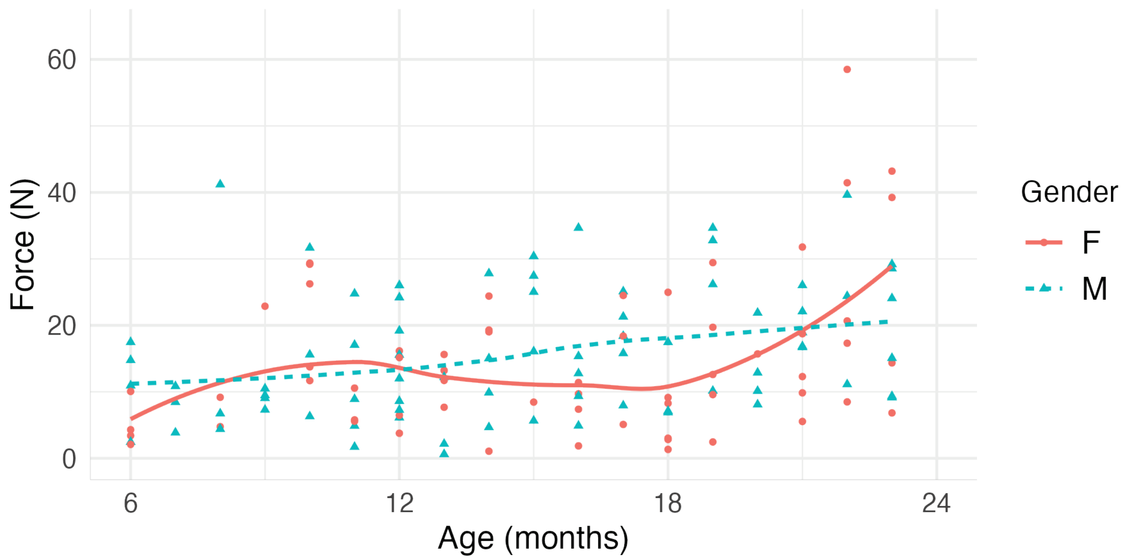
Configuration: Stand, Lap, Booster, or Floor

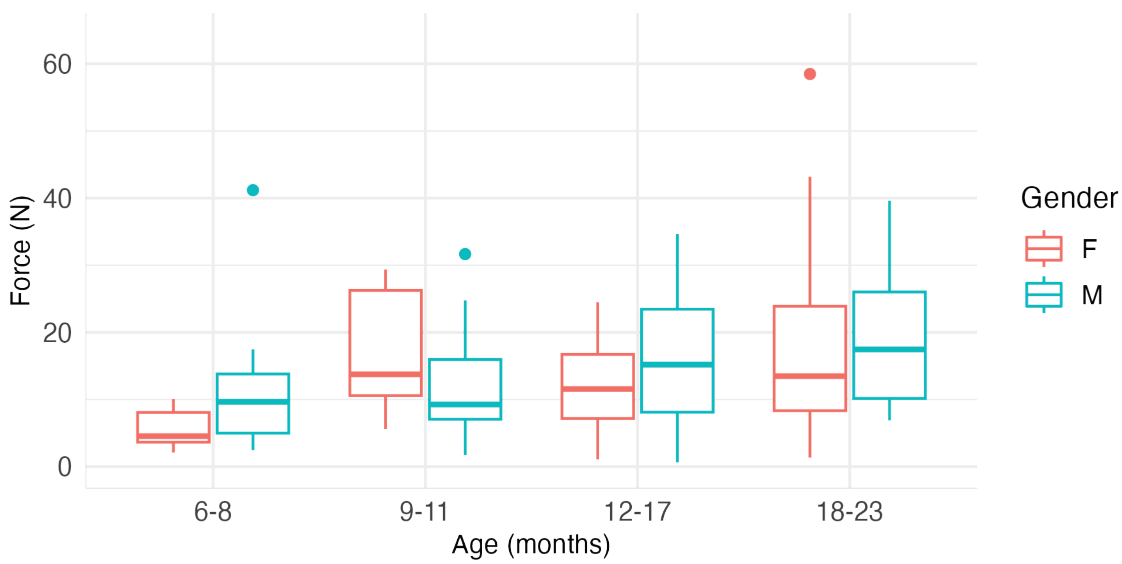
Posture: Pull with one or two hands

Interface: Squishy

Units: Newton

Squishy_ToW_Pull





Squishy_ToW_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	12.1	11.3	2.4	3.1	9.7	30.5	41.2
6-8	0.50-0.74	F	6	5.6	3.2	2.1	2.4	4.5	9.8	10.1
6-8	0.50-0.74	Both	16	9.7	9.5	2.1	2.4	7.6	23.4	41.2
9-11	0.75-0.99	M	12	12.3	8.7	1.7	3.5	9.3	27.9	31.7
9-11	0.75-0.99	F	9	17.2	9.7	5.6	5.7	13.8	29.3	29.4
9-11	0.75-0.99	Both	21	14.4	9.2	1.7	4.9	10.6	29.4	31.7
12-17	1.00-1.49	M	30	15.4	9.1	0.6	3.3	15.2	29.2	34.7
12-17	1.00-1.49	F	20	12.0	7.0	1.1	1.8	11.6	24.4	24.5
12-17	1.00-1.49	Both	50	14.0	8.4	0.6	2.0	13.0	27.6	34.7
18-23	1.50-1.99	M	25	19.2	9.4	6.9	7.3	17.5	34.3	39.6
18-23	1.50-1.99	F	26	18.0	14.7	1.3	2.6	13.5	42.8	58.5
18-23	1.50-1.99	Both	51	18.6	12.3	1.3	2.9	16.7	40.5	58.5

Bubble_Push

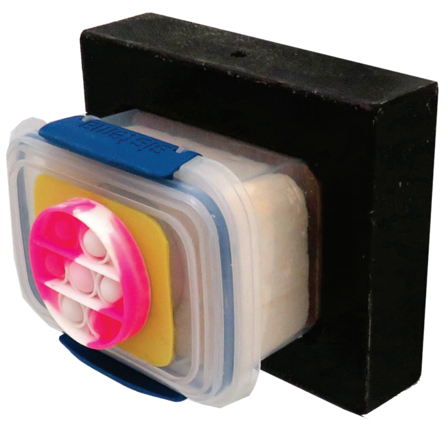
Description: Standing or Seated

Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

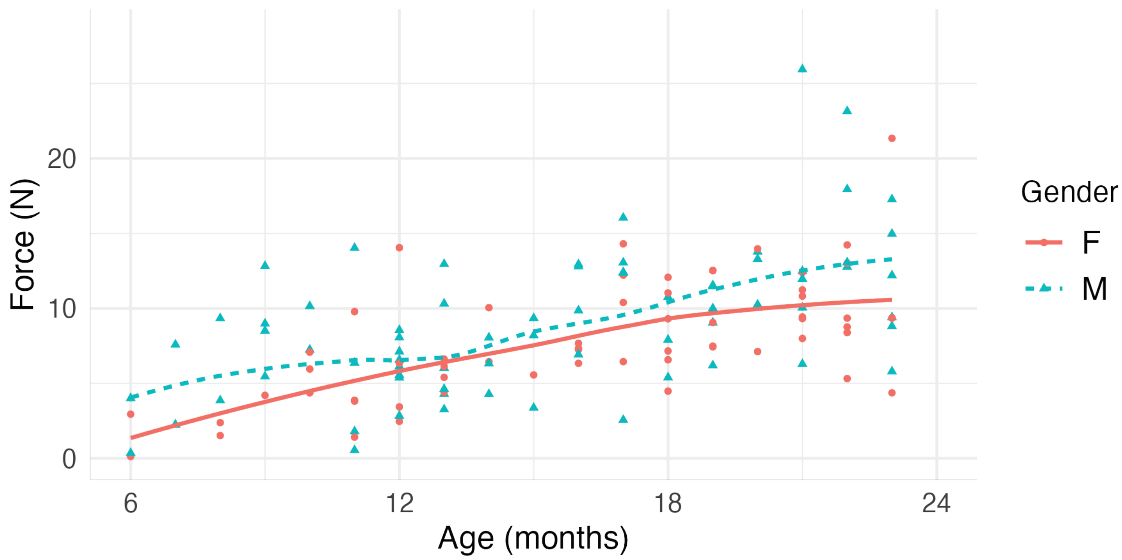
Posture: Push with one or two hands

Interface: Bubble

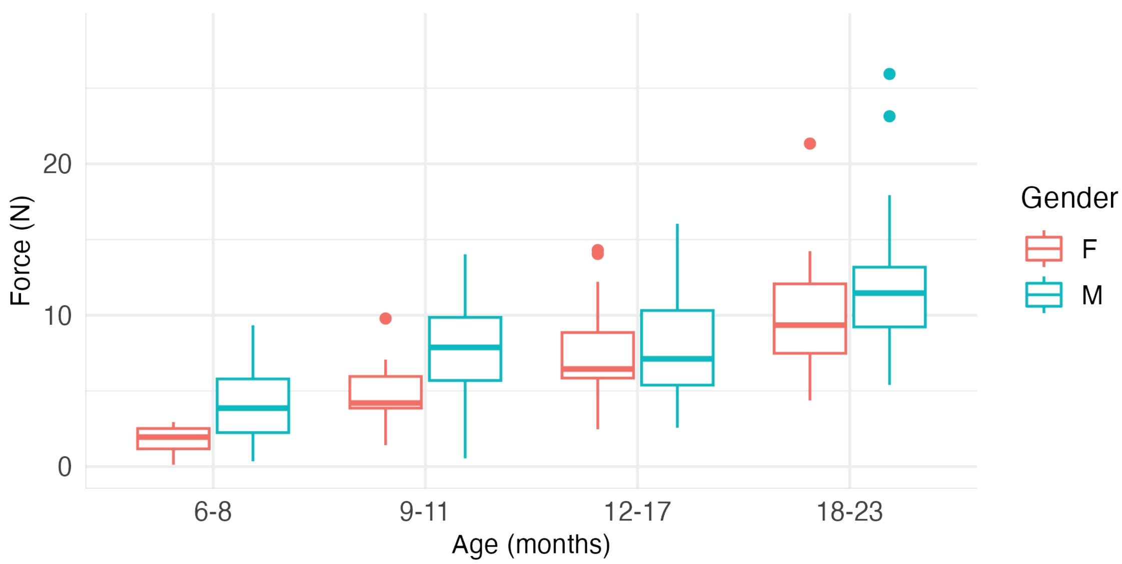
Units: Newton



Bubble_Push



Force (N)
0
10
20
6
12
18
24
Age (months)
Gender
F
M



Force (N)
0
10
20
6-8
9-11
12-17
18-23
Age (months)
Gender
F
M

Bubble_Push (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	7	4.2	3.2	0.4	0.9	3.9	8.8	9.3
6-8	0.50-0.74	F	4	1.7	1.2	0.1	0.3	1.9	2.9	2.9
6-8	0.50-0.74	Both	11	3.3	2.8	0.1	0.2	2.4	8.5	9.3
9-11	0.75-0.99	M	10	7.6	4.3	0.5	1.1	7.9	13.5	14.0
9-11	0.75-0.99	F	9	4.9	2.4	1.4	2.4	4.2	8.7	9.8
9-11	0.75-0.99	Both	19	6.3	3.7	0.5	1.3	6.0	12.9	14.0
12-17	1.00-1.49	M	29	7.9	3.7	2.6	3.0	7.1	13.0	16.0
12-17	1.00-1.49	F	19	7.5	3.3	2.5	3.3	6.4	14.1	14.3
12-17	1.00-1.49	Both	48	7.8	3.5	2.5	3.0	6.8	13.7	16.0
18-23	1.50-1.99	M	27	11.9	4.8	5.4	5.9	11.5	21.6	25.9
18-23	1.50-1.99	F	29	9.8	3.5	4.4	4.8	9.3	14.1	21.3
18-23	1.50-1.99	Both	56	10.8	4.3	4.4	5.4	10.0	18.8	25.9

Bowl_Push

Description: Standing or Seated

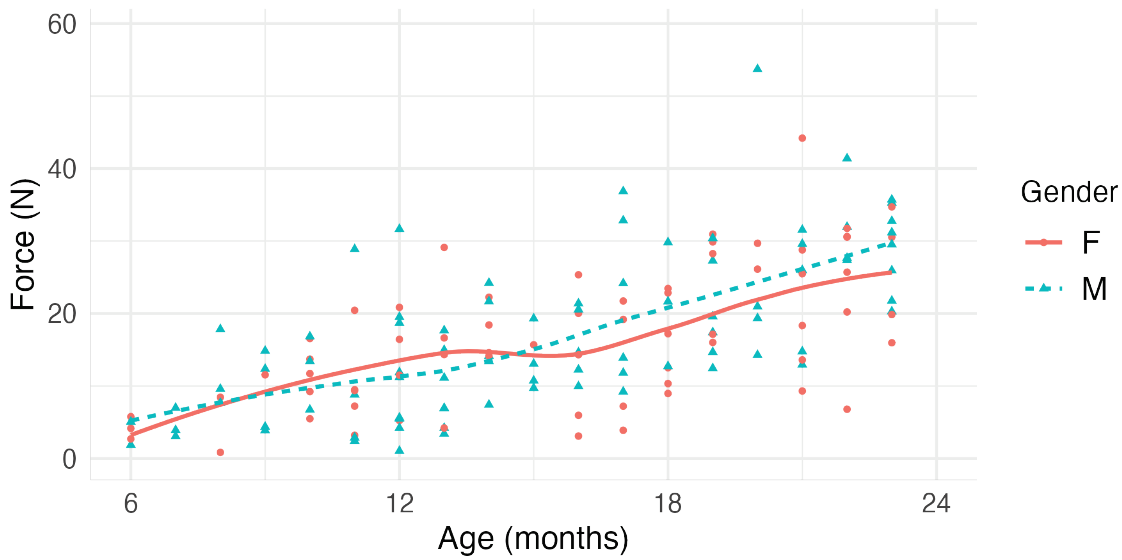
Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

Posture: Push with one or two hands

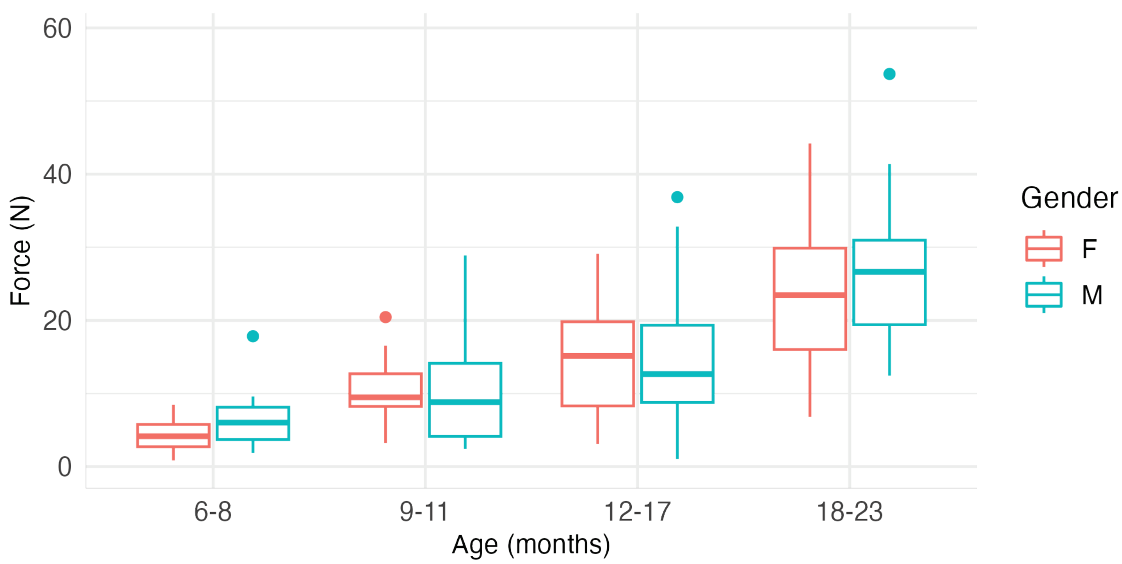
Interface: Bowl

Units: Newton

Bowl_Push



Force (N)
60
40
20
0
6
12
18
24
Age (months)
Gender
F
M



Force (N)
60
40
20
0
6-8
9-11
12-17
18-23
Age (months)
Gender
F
M

Bowl_Push (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	8	7.0	5.1	1.9	2.3	6.0	14.9	17.8
6-8	0.50-0.74	F	5	4.4	2.9	0.8	1.2	4.2	7.9	8.5
6-8	0.50-0.74	Both	13	6.0	4.4	0.8	1.5	5.1	12.9	17.8
9-11	0.75-0.99	M	11	10.5	7.9	2.4	2.6	8.8	22.9	28.9
9-11	0.75-0.99	F	11	10.7	4.9	3.2	4.3	9.5	18.5	20.4
9-11	0.75-0.99	Both	22	10.6	6.4	2.4	2.9	9.4	20.3	28.9
12-17	1.00-1.49	M	36	14.3	8.5	1.0	4.0	12.7	31.9	36.9
12-17	1.00-1.49	F	22	14.7	7.3	3.1	3.9	15.1	25.2	29.1
12-17	1.00-1.49	Both	58	14.5	8.0	1.0	3.8	14.1	29.5	36.9
18-23	1.50-1.99	M	30	25.7	9.4	12.4	12.8	26.6	38.8	53.7
18-23	1.50-1.99	F	29	22.8	9.0	6.8	9.1	23.4	33.5	44.2
18-23	1.50-1.99	Both	59	24.2	9.3	6.8	10.2	25.7	36.3	53.7

ShapeBoard_Push

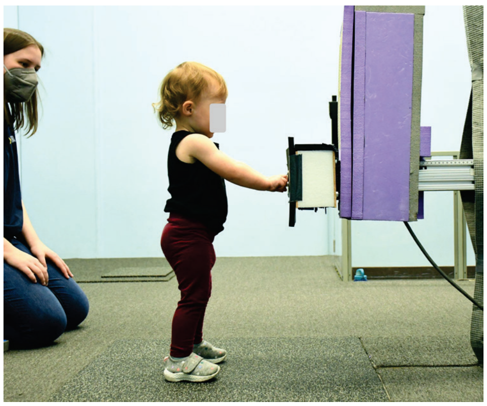
Description: Standing or Seated

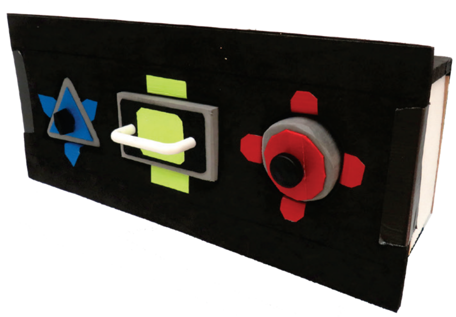
Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

Posture: Push with one or two hands

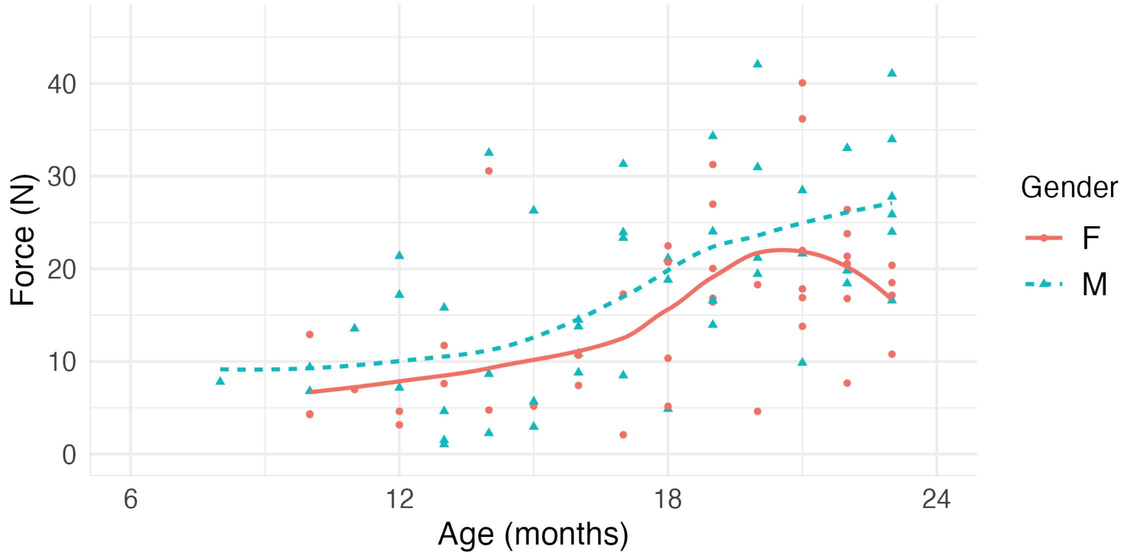
Interface: WhiteHandle_ShapeBoard

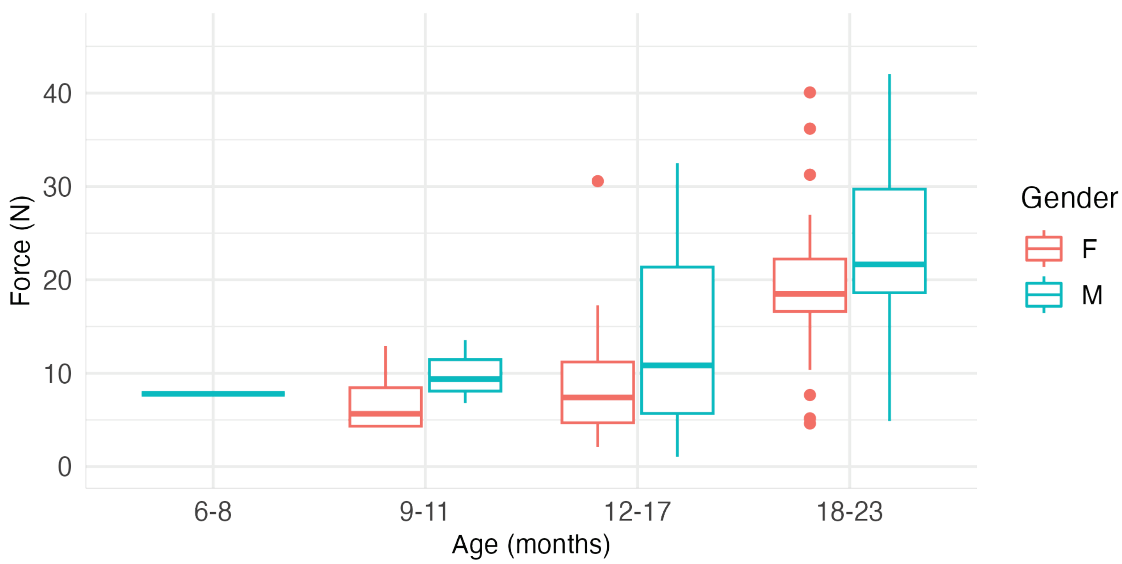
Units: Newton





ShapeBoard_Push





ShapeBoard_Push (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	1	7.8		7.8	7.8	7.8	7.8	7.8
6-8	0.50-0.74	F	0							
6-8	0.50-0.74	Both	1	7.8		7.8	7.8	7.8	7.8	7.8
9-11	0.75-0.99	M	3	9.9	3.4	6.8	7.1	9.4	13.1	13.5
9-11	0.75-0.99	F	4	7.1	4.1	4.3	4.3	5.7	12.0	12.9
9-11	0.75-0.99	Both	7	8.3	3.8	4.3	4.3	7.0	13.4	13.5
12-17	1.00-1.49	M	21	13.4	9.8	1.1	1.5	10.8	31.3	32.5
12-17	1.00-1.49	F	11	9.6	8.2	2.1	2.6	7.4	23.9	30.6
12-17	1.00-1.49	Both	32	12.1	9.3	1.1	1.8	8.7	30.9	32.5
18-23	1.50-1.99	M	23	23.8	9.3	4.9	10.3	21.6	40.4	42.0
18-23	1.50-1.99	F	27	19.4	8.3	4.6	5.9	18.5	34.7	40.1
18-23	1.50-1.99	Both	50	21.4	8.9	4.6	6.3	20.5	38.3	42.0

SensoryBoard_Push

Description: Standing or Seated

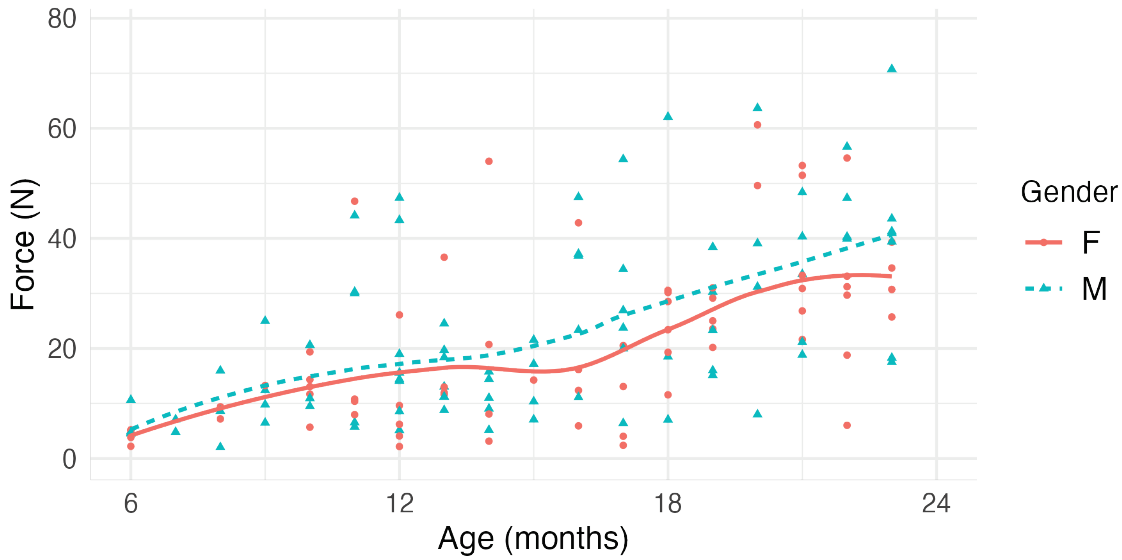
Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

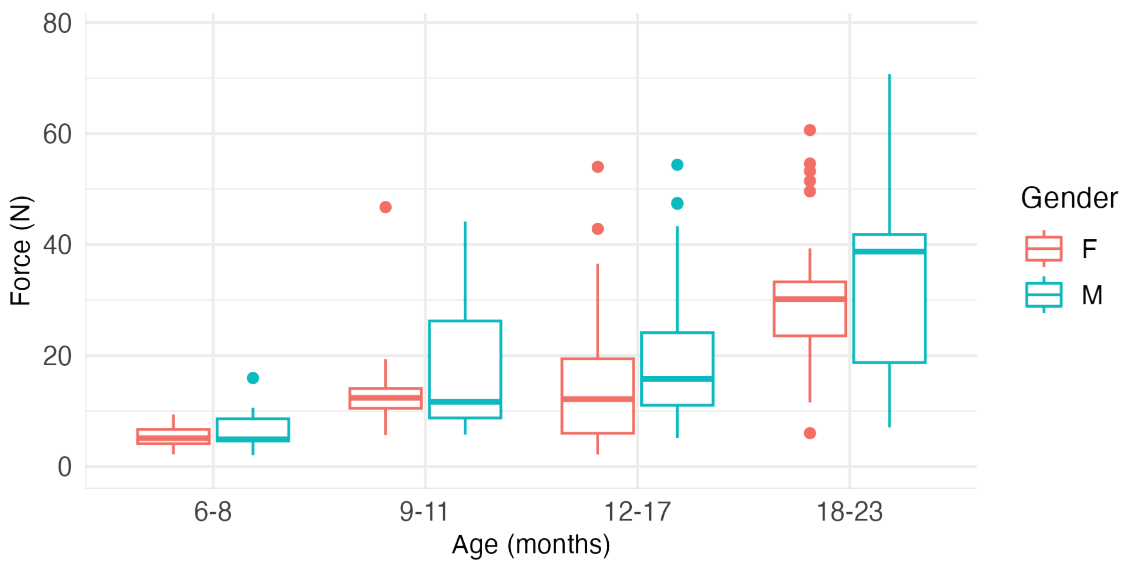
Posture: Push with one or two hands

Interface: SensoryBoard

Units: Newton

SensoryBoard_Push





SensoryBoard_Push (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	9	7.0	4.2	2.0	3.0	4.9	13.8	16.0
6-8	0.50-0.74	F	6	5.5	2.5	2.2	2.6	5.1	8.8	9.4
6-8	0.50-0.74	Both	15	6.4	3.6	2.0	2.2	5.0	12.2	16.0
9-11	0.75-0.99	M	12	17.6	12.3	5.8	6.2	11.7	36.5	44.1
9-11	0.75-0.99	F	10	15.3	11.6	5.7	6.7	12.4	34.4	46.7
9-11	0.75-0.99	Both	22	16.6	11.8	5.7	5.8	12.1	43.5	46.7
12-17	1.00-1.49	M	35	20.2	13.2	5.1	6.0	15.8	47.4	54.4
12-17	1.00-1.49	F	22	15.4	13.7	2.2	2.4	12.2	42.5	54.0
12-17	1.00-1.49	Both	57	18.4	13.4	2.2	3.9	14.3	47.4	54.4
18-23	1.50-1.99	M	28	34.7	16.8	7.1	10.5	38.7	63.1	70.7
18-23	1.50-1.99	F	29	31.2	12.7	6.0	14.5	30.2	54.0	60.6
18-23	1.50-1.99	Both	57	32.9	14.8	6.0	10.9	30.9	60.9	70.7

Spinner_Down

Description: Standing or Seated

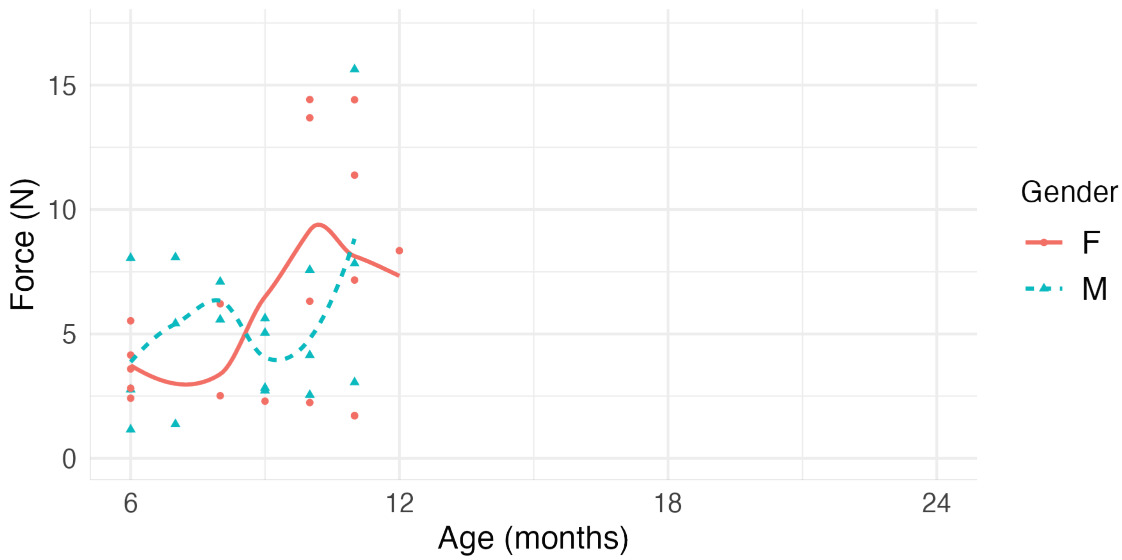
Configuration: Floor

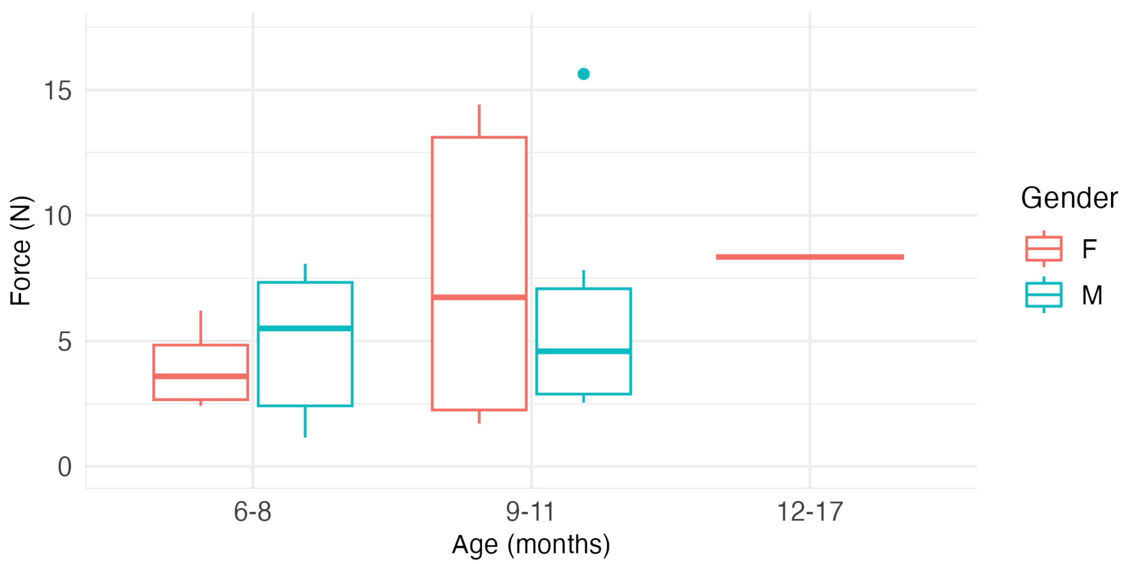
Posture: Downward exertion with one or two hands

Interface: Spinner

Units: Newton

Spinner_Down





Spinner_Down (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	8	4.9	2.8	1.2	1.2	5.5	8.1	8.1
6-8	0.50-0.74	F	7	3.9	1.5	2.4	2.4	3.6	6.0	6.2
6-8	0.50-0.74	Both	15	4.5	2.3	1.2	1.3	4.2	8.1	8.1
9-11	0.75-0.99	M	10	5.7	4.0	2.5	2.6	4.6	12.1	15.6
9-11	0.75-0.99	F	10	7.5	5.5	1.7	1.7	6.7	14.4	14.4
9-11	0.75-0.99	Both	20	6.6	4.8	1.7	1.7	5.3	14.5	15.6
12-17	1.00-1.49	M	0							
12-17	1.00-1.49	F	1	8.3		8.3	8.3	8.3	8.3	8.3
12-17	1.00-1.49	Both	1	8.3		8.3	8.3	8.3	8.3	8.3
18-23	1.50-1.99	M	0							
18-23	1.50-1.99	F	0							
18-23	1.50-1.99	Both	0							

Dynamometer_24mm_Grip

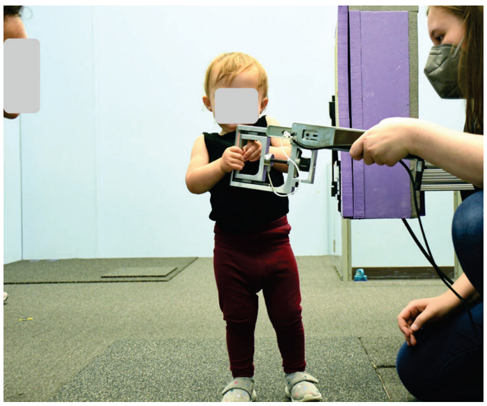
Description: Standing or Seated

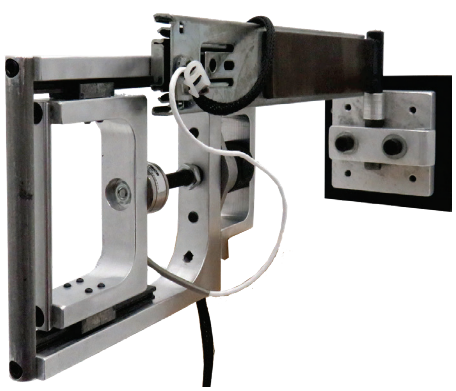
Configuration: Elbow_Stand or Elbow_Seated

Posture: Grip exertion with one hand

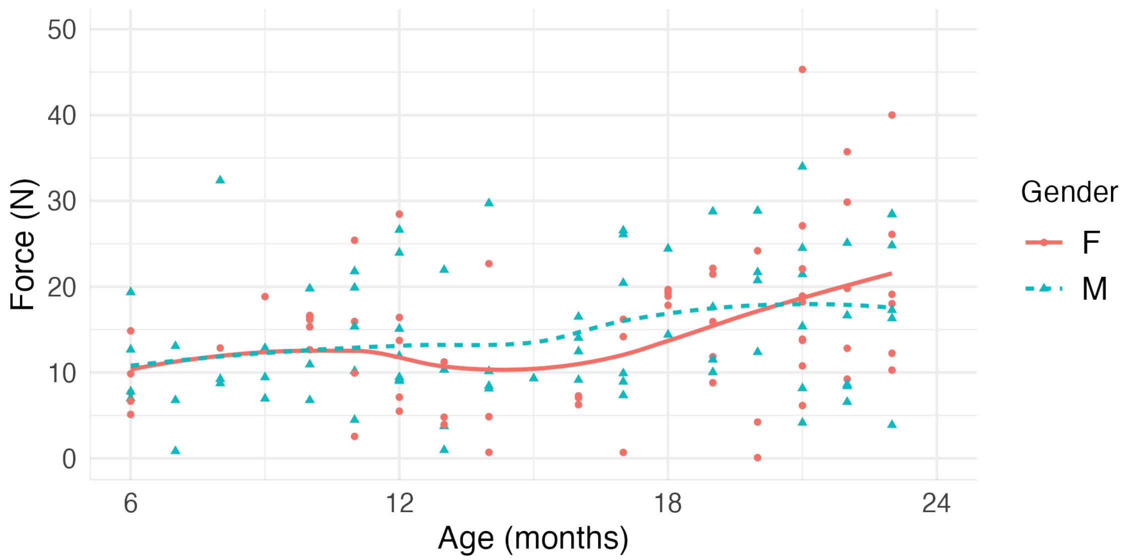
Interface: Dynamometer_24

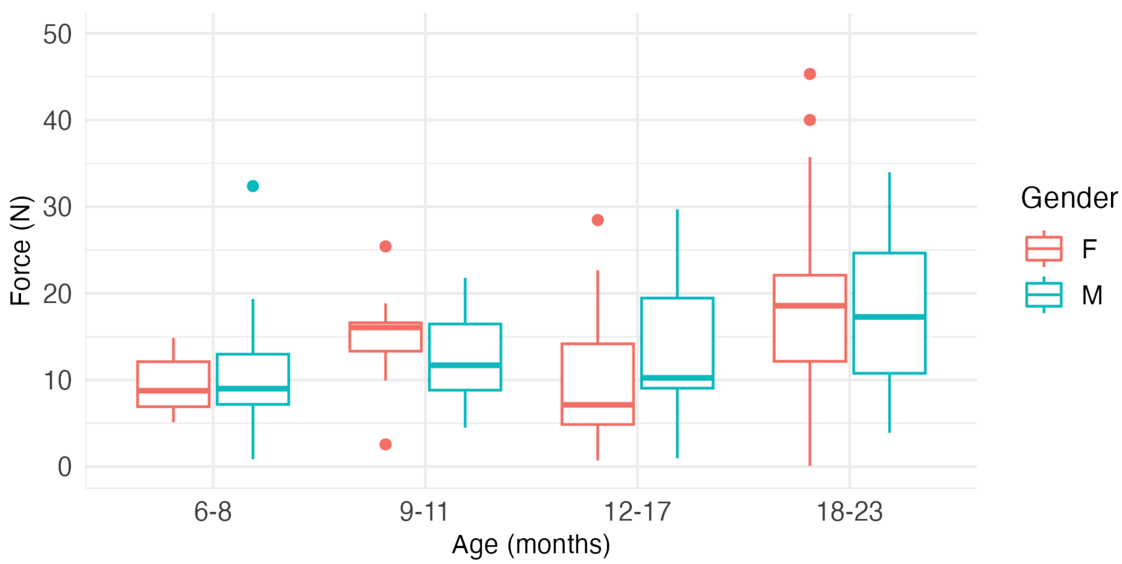
Units: Newton





Dynamometer_24mm_Grip





Dynamometer_24mm_Grip (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	11.8	8.7	0.8	3.5	9.0	26.5	32.4
6-8	0.50-0.74	F	6	9.5	3.8	5.1	5.5	8.8	14.4	14.9
6-8	0.50-0.74	Both	16	10.9	7.2	0.8	4.1	9.0	22.6	32.4
9-11	0.75-0.99	M	12	12.6	5.6	4.5	5.7	11.7	20.7	21.8
9-11	0.75-0.99	F	10	15.0	5.9	2.6	5.9	16.1	22.5	25.4
9-11	0.75-0.99	Both	22	13.7	5.8	2.6	4.6	14.1	21.7	25.4
12-17	1.00-1.49	M	26	13.8	7.7	1.0	4.6	10.2	26.6	29.7
12-17	1.00-1.49	F	17	10.1	7.6	0.7	0.7	7.1	23.8	28.5
12-17	1.00-1.49	Both	43	12.3	7.8	0.7	1.2	9.9	26.6	29.7
18-23	1.50-1.99	M	27	17.9	8.5	3.9	4.9	17.3	28.8	34.0
18-23	1.50-1.99	F	32	18.6	9.8	0.1	5.3	18.6	37.7	45.3
18-23	1.50-1.99	Both	59	18.2	9.2	0.1	4.2	18.0	34.2	45.3

Pegboard_Pull

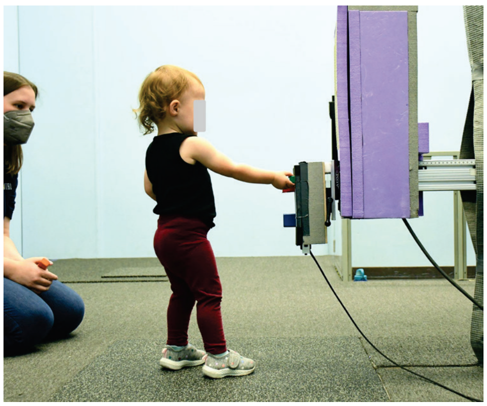
Description: Standing or Seated

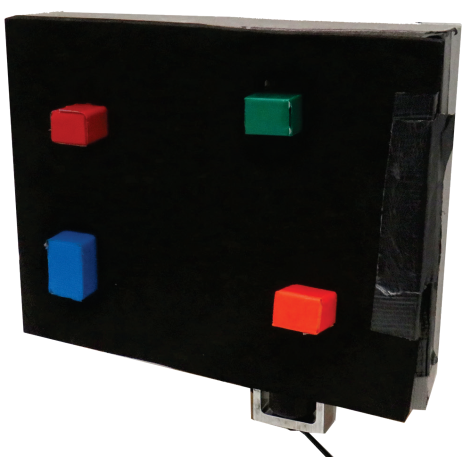
Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

Posture: Pinch-pull with one or two hands

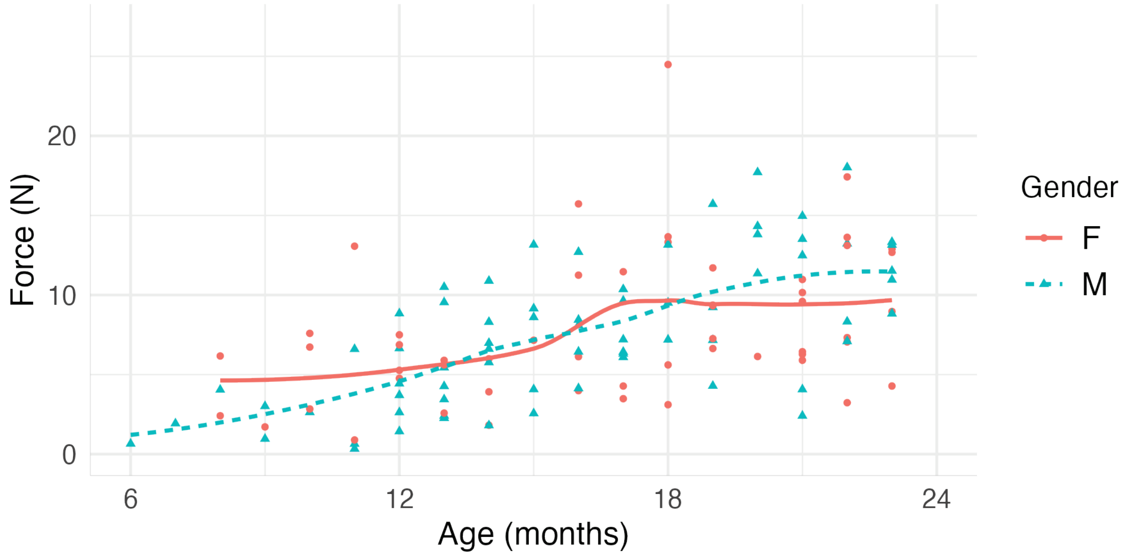
Interface: Pegboard

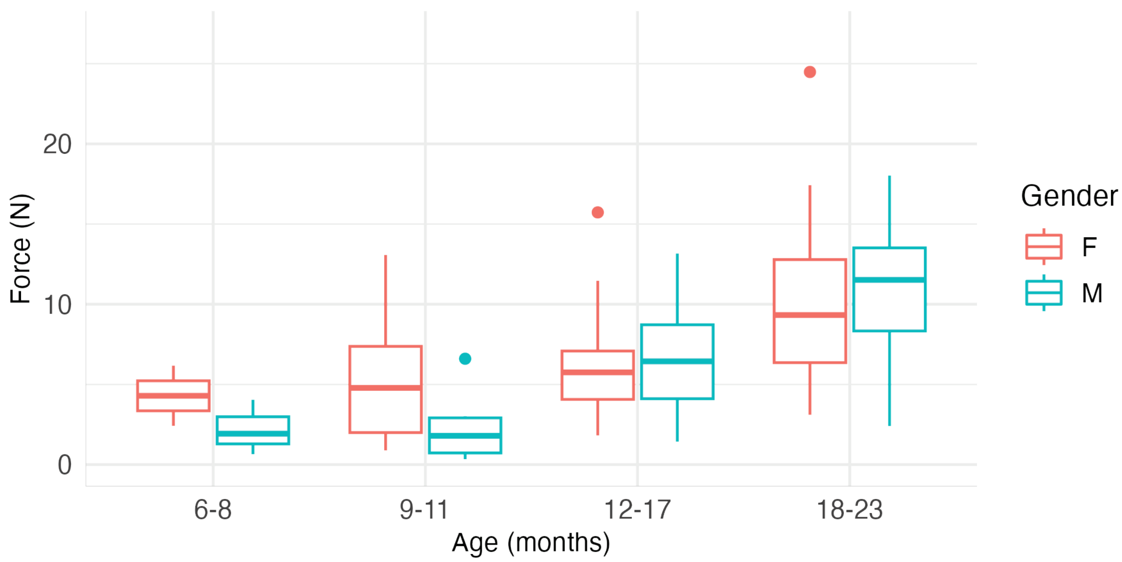
Units: Newton





Pegboard_Pull





Pegboard_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	3	2.2	1.7	0.7	0.8	1.9	3.8	4.0
6-8	0.50-0.74	F	2	4.3	2.7	2.4	2.6	4.3	6.0	6.2
6-8	0.50-0.74	Both	5	3.0	2.1	0.7	0.9	2.4	5.7	6.2
9-11	0.75-0.99	M	6	2.4	2.3	0.3	0.4	1.8	5.7	6.6
9-11	0.75-0.99	F	6	5.5	4.6	0.9	1.1	4.8	11.7	13.1
9-11	0.75-0.99	Both	12	3.9	3.8	0.3	0.5	2.7	10.1	13.1
12-17	1.00-1.49	M	35	6.6	3.1	1.4	2.1	6.4	11.4	13.2
12-17	1.00-1.49	F	18	6.3	3.5	1.8	2.5	5.8	12.1	15.7
12-17	1.00-1.49	Both	53	6.5	3.2	1.4	2.1	6.1	12.0	15.7
18-23	1.50-1.99	M	25	11.0	4.1	2.4	4.1	11.5	17.3	18.0
18-23	1.50-1.99	F	27	9.6	4.7	3.1	3.5	9.3	16.3	24.5
18-23	1.50-1.99	Both	52	10.3	4.4	2.4	3.7	9.9	17.6	24.5

GearRotation_CW

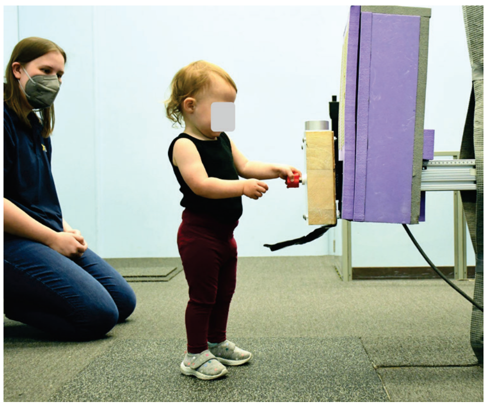
Description: Standing or Seated

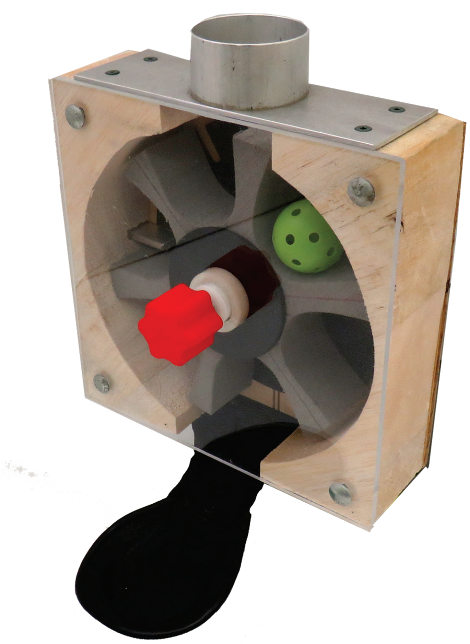
Configuration: Elbow_Stand, Chest_Lap, Chest_Booster, or Chest_Floor

Posture: Clockwise twist with one or two hands

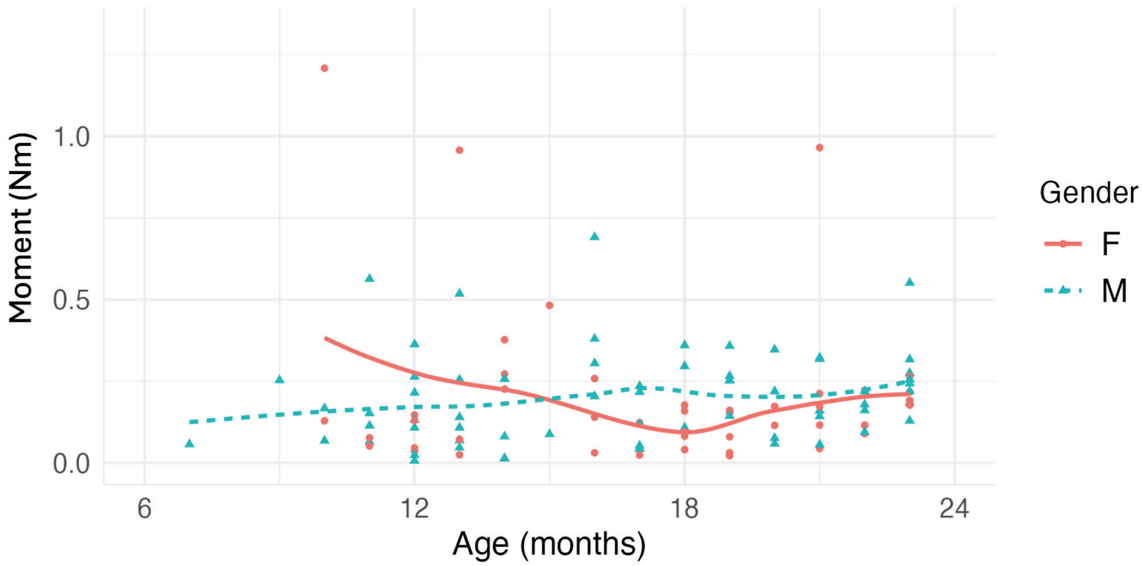
Interface: GearRotation

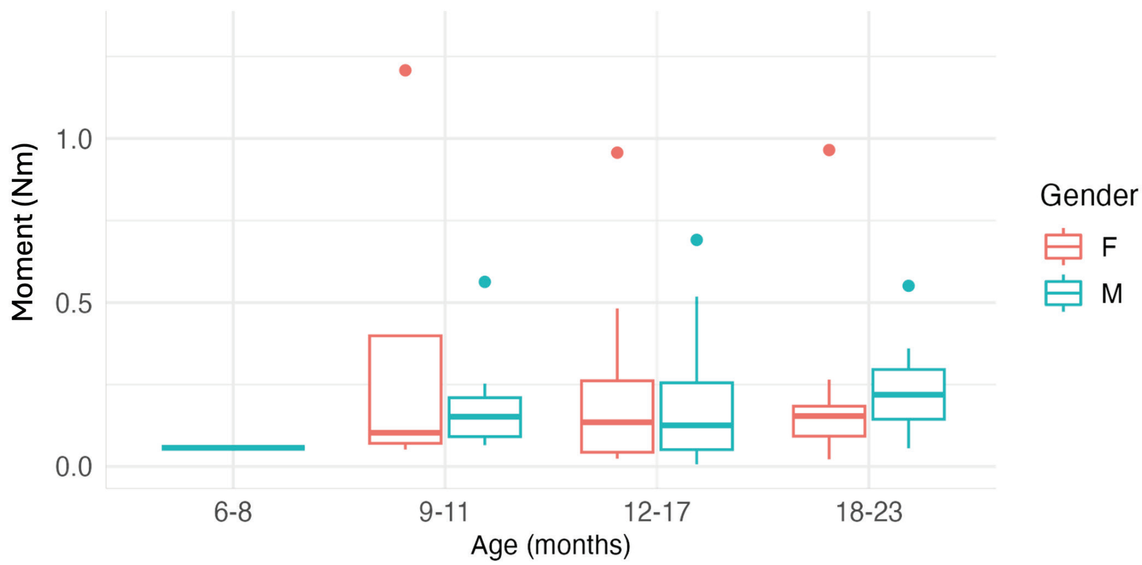
Units: Newton-meter





GearRotation_CW





GearRotation_CW (Nm)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	1	0.1		0.1	0.1	0.1	0.1	0.1
6-8	0.50-0.74	F	0							
6-8	0.50-0.74	Both	1	0.1		0.1	0.1	0.1	0.1	0.1
9-11	0.75-0.99	M	7	0.2	0.2	0.1	0.1	0.2	0.5	0.6
9-11	0.75-0.99	F	4	0.4	0.6	0.1	0.1	0.1	1.0	1.2
9-11	0.75-0.99	Both	11	0.3	0.3	0.1	0.1	0.1	0.9	1.2
12-17	1.00-1.49	M	28	0.2	0.2	0.0	0.0	0.1	0.5	0.7
12-17	1.00-1.49	F	16	0.2	0.2	0.0	0.0	0.1	0.6	1.0
12-17	1.00-1.49	Both	44	0.2	0.2	0.0	0.0	0.1	0.5	1.0
18-23	1.50-1.99	M	29	0.2	0.1	0.1	0.1	0.2	0.4	0.6
18-23	1.50-1.99	F	27	0.2	0.2	0.0	0.0	0.2	0.3	1.0
18-23	1.50-1.99	Both	56	0.2	0.1	0.0	0.0	0.2	0.4	1.0

PullApart_Knob_32mm_Pull

Description: Standing or Seated

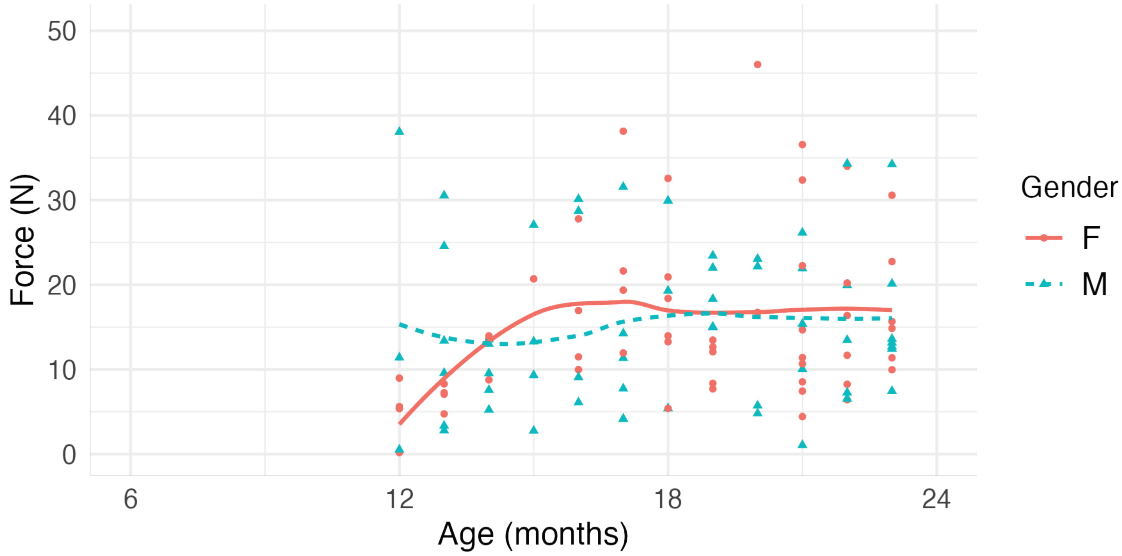
Configuration: Elbow_Stand

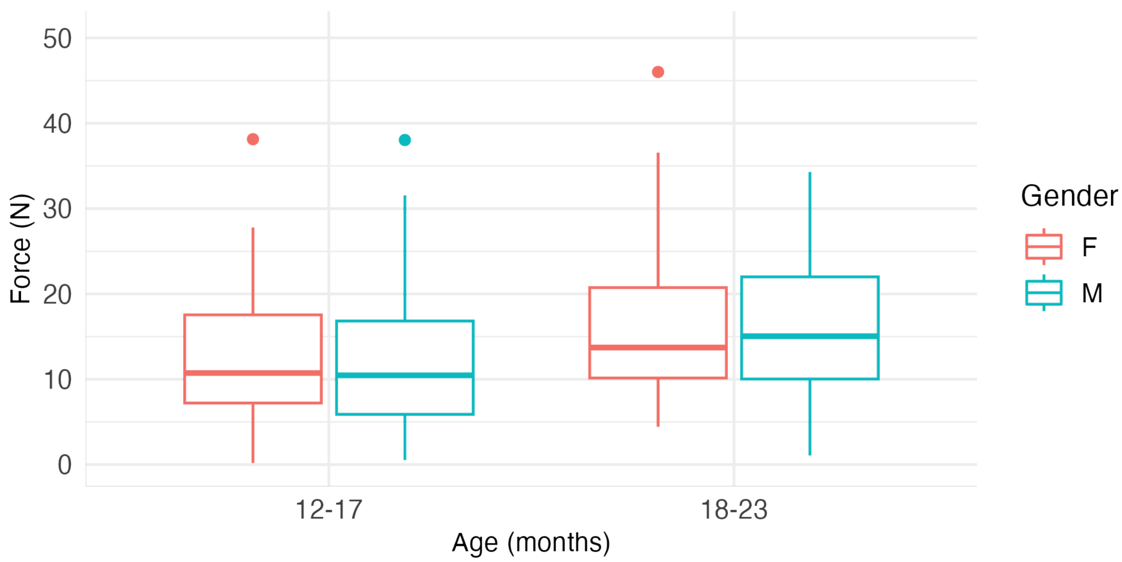
Posture: Two-hand opposed pull

Interface: PullApart_32

Units: Newton

PullApart_Knob_32mm_Pull





PullApart_Knob_32mm_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	0							
6-8	0.50-0.74	F	0							
6-8	0.50-0.74	Both	0							
9-11	0.75-0.99	M	0							
9-11	0.75-0.99	F	0							
9-11	0.75-0.99	Both	0							
12-17	1.00-1.49	M	28	13.7	10.5	0.5	2.8	10.5	31.2	38.0
12-17	1.00-1.49	F	20	13.1	9.0	0.2	4.5	10.7	28.3	38.1
12-17	1.00-1.49	Both	48	13.4	9.8	0.2	2.8	10.7	31.2	38.1
18-23	1.50-1.99	M	29	16.3	8.7	1.1	5.0	15.0	32.5	34.3
18-23	1.50-1.99	F	34	16.8	10.1	4.4	6.1	13.7	34.9	46.0
18-23	1.50-1.99	Both	63	16.6	9.4	1.1	5.4	14.7	34.2	46.0

Cruise_Pull

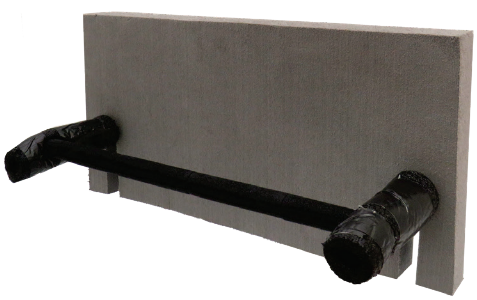
Description: Standing

Configuration: Elbow_Stand

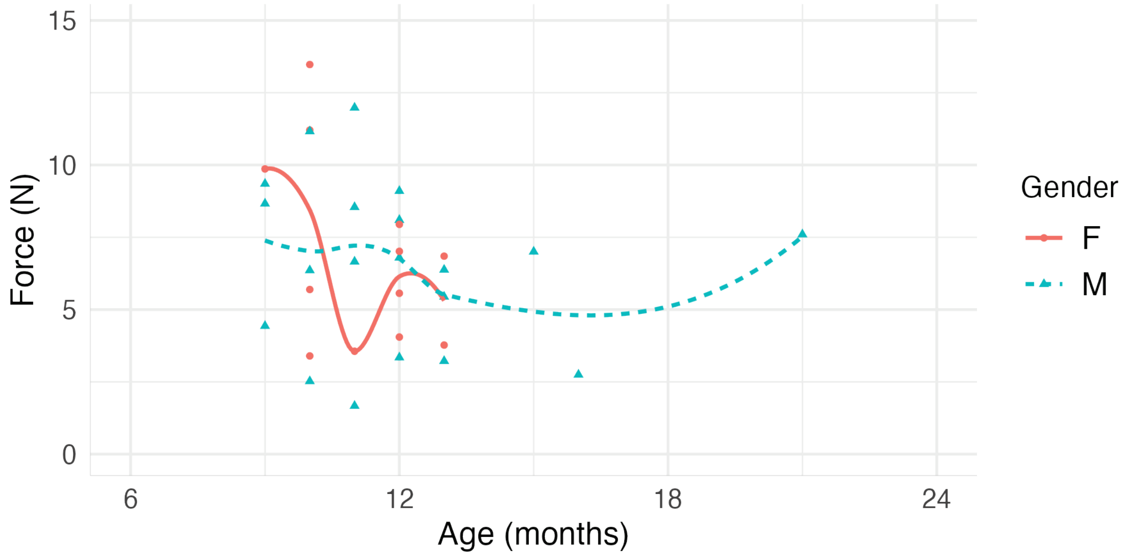
Posture: Pull with one or two hands

Interface: Bar

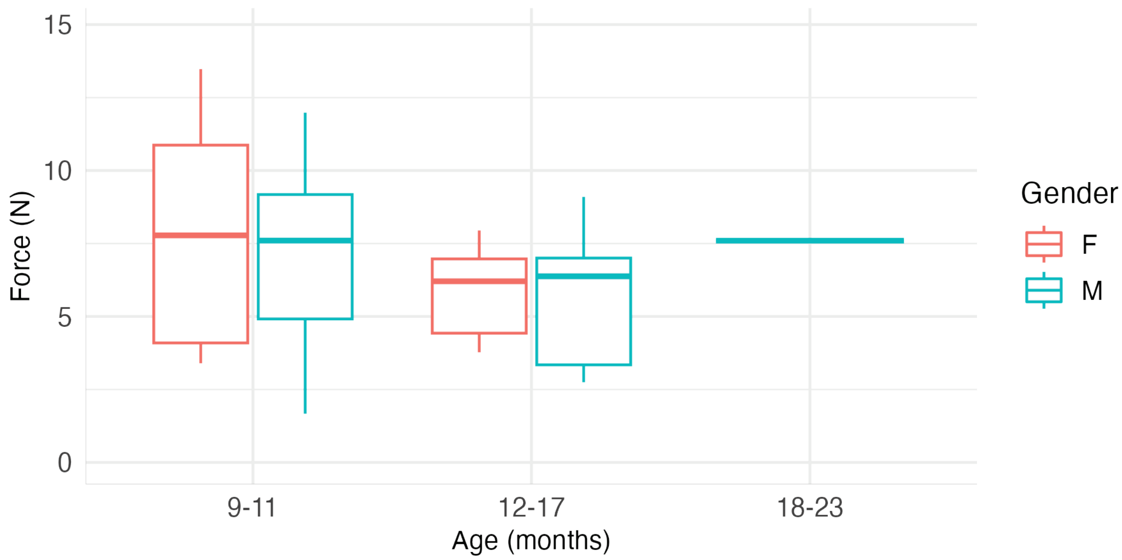
Units: Newton



Cruise_Pull



15
10
5
0
Force (N)
6
12
18
24
Age (months)
Gender
F
M



15
10
5
0
Force (N)
9-11
12-17
18-23
Age (months)
Gender
F
M

Cruise_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	0							
6-8	0.50-0.74	F	0							
6-8	0.50-0.74	Both	0							
9-11	0.75-0.99	M	10	7.1	3.5	1.7	2.1	7.6	11.6	12.0
9-11	0.75-0.99	F	6	7.9	4.2	3.4	3.4	7.8	12.9	13.5
9-11	0.75-0.99	Both	16	7.4	3.7	1.7	2.3	7.6	12.4	13.5
12-17	1.00-1.49	M	9	5.8	2.3	2.7	2.9	6.4	8.7	9.1
12-17	1.00-1.49	F	6	5.9	1.7	3.8	3.8	6.2	7.7	7.9
12-17	1.00-1.49	Both	15	5.8	2.0	2.7	3.1	6.4	8.4	9.1
18-23	1.50-1.99	M	1	7.6		7.6	7.6	7.6	7.6	7.6
18-23	1.50-1.99	F	0							
18-23	1.50-1.99	Both	1	7.6		7.6	7.6	7.6	7.6	7.6

SitStand_Pull

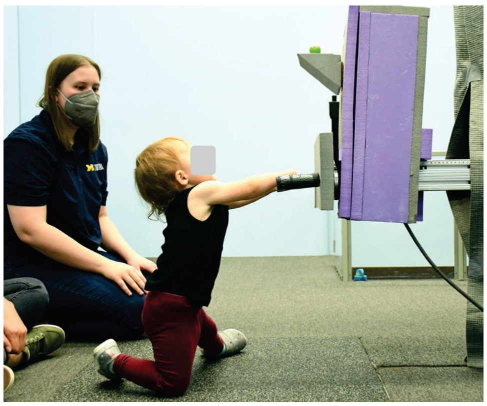
Description: Standing

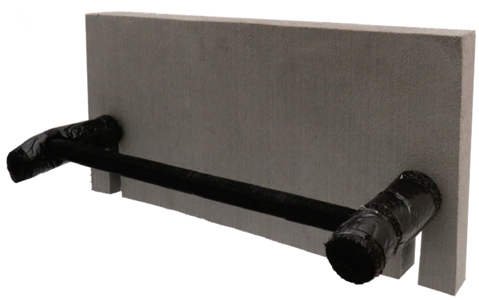
Configuration: Elbow_Stand

Posture: Downward exertion with one or two hands

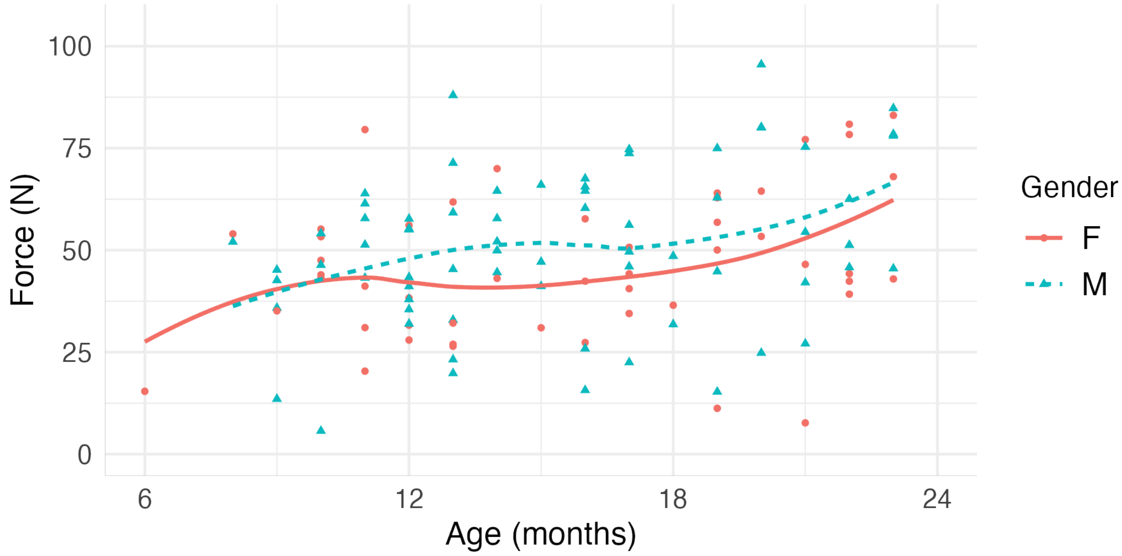
Interface: Bar

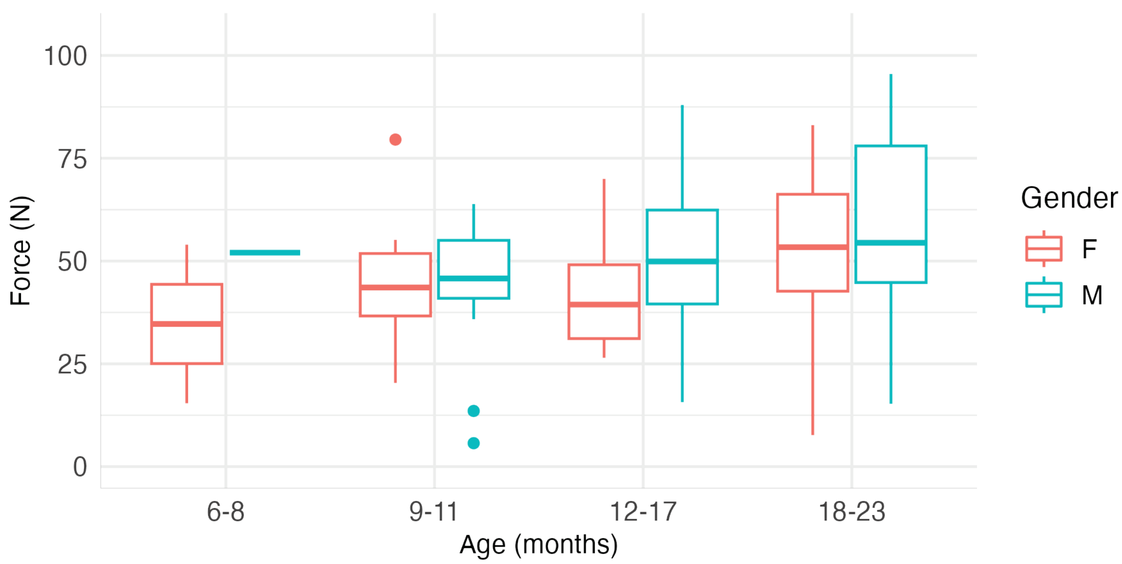
Units: Newton *Resultant Force





SitStand_Pull





SitStand_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	1	52.0		52.0	52.0	52.0	52.0	52.0
6-8	0.50-0.74	F	2	34.7	27.3	15.4	17.3	34.7	52.1	54.0
6-8	0.50-0.74	Both	3	40.5	21.7	15.4	19.1	52.0	53.8	54.0
9-11	0.75-0.99	M	12	43.4	17.9	5.7	10.0	45.8	62.5	63.9
9-11	0.75-0.99	F	10	45.0	16.0	20.3	25.1	43.6	68.6	79.5
9-11	0.75-0.99	Both	22	44.1	16.6	5.7	13.9	44.6	63.8	79.5
12-17	1.00-1.49	M	35	49.8	17.2	15.7	21.7	49.9	74.0	88.0
12-17	1.00-1.49	F	18	41.3	13.2	26.5	26.9	39.4	63.0	70.0
12-17	1.00-1.49	Both	53	46.9	16.4	15.7	22.9	45.3	72.3	88.0
18-23	1.50-1.99	M	21	57.3	22.3	15.3	24.8	54.4	84.8	95.5
18-23	1.50-1.99	F	19	53.1	21.2	7.7	10.9	53.4	81.1	83.0
18-23	1.50-1.99	Both	40	55.3	21.6	7.7	15.1	53.9	83.1	95.5

Prone_AssistedPull

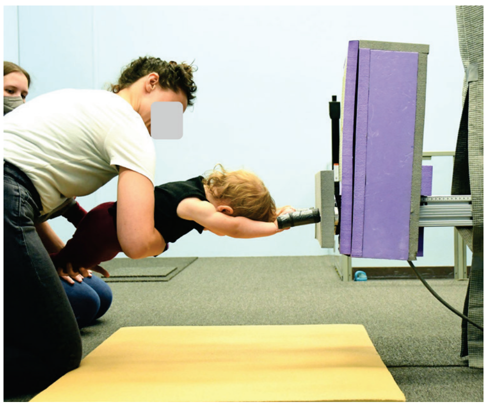
Description: Standing

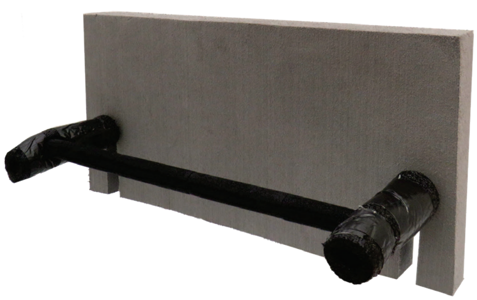
Configuration: LowerTorso_Stand

Posture: Grip exertion with one or two hands

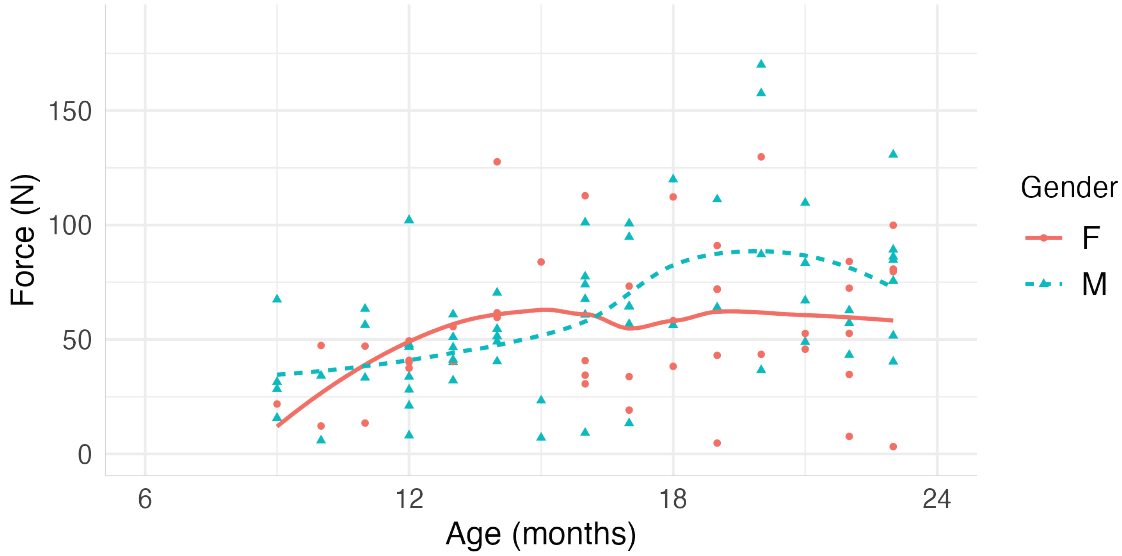
Interface: Bar

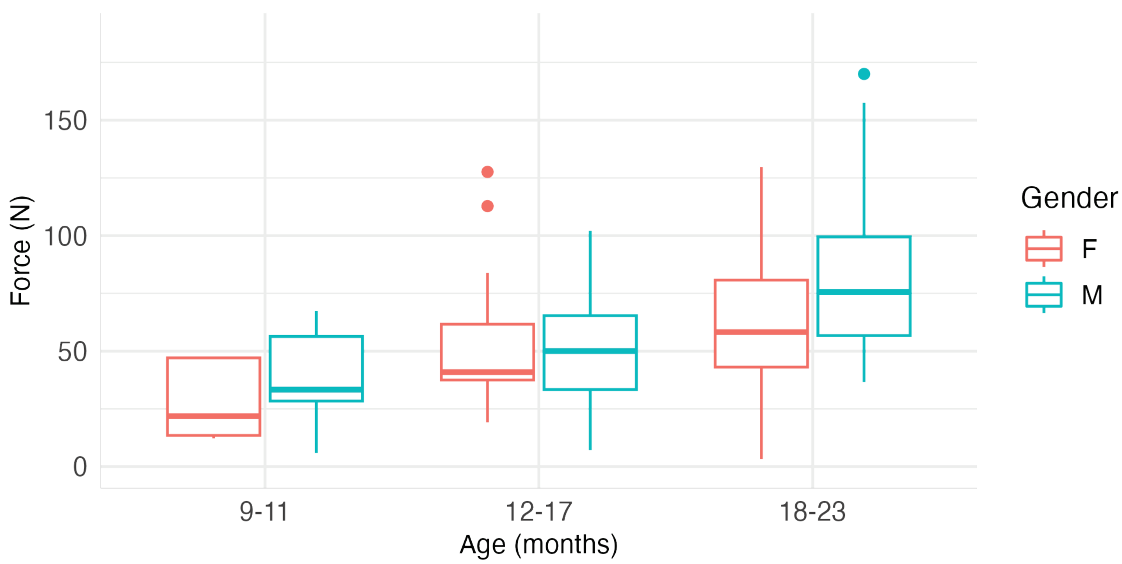
Units: Newton





Prone_AssistedPull





Prone_AssistedPull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	0							
6-8	0.50-0.74	F	0							
6-8	0.50-0.74	Both	0							
9-11	0.75-0.99	M	9	37.4	21.0	5.9	9.8	33.3	65.8	67.5
9-11	0.75-0.99	F	5	28.4	17.6	12.2	12.5	21.8	47.3	47.4
9-11	0.75-0.99	Both	14	34.2	19.7	5.9	10.0	32.4	64.8	67.5
12-17	1.00-1.49	M	32	51.3	26.7	7.1	8.7	50.1	100.9	102.1
12-17	1.00-1.49	F	17	55.4	29.3	19.2	28.4	40.9	115.7	127.6
12-17	1.00-1.49	Both	49	52.7	27.4	7.1	10.9	49.1	101.7	127.6
18-23	1.50-1.99	M	23	82.4	36.2	36.6	40.6	75.6	154.8	170.0
18-23	1.50-1.99	F	21	60.9	33.9	3.2	4.8	58.2	112.3	129.8
18-23	1.50-1.99	Both	44	72.1	36.4	3.2	11.7	69.5	130.6	170.0

DynamicBar_Pull

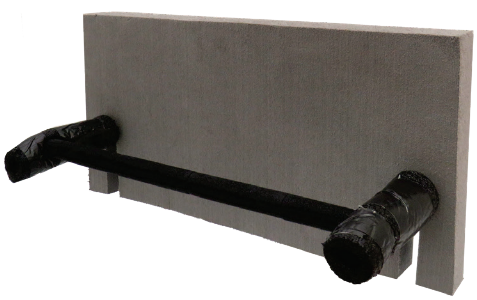
Description: Standing

Configuration: Elbow_Stand

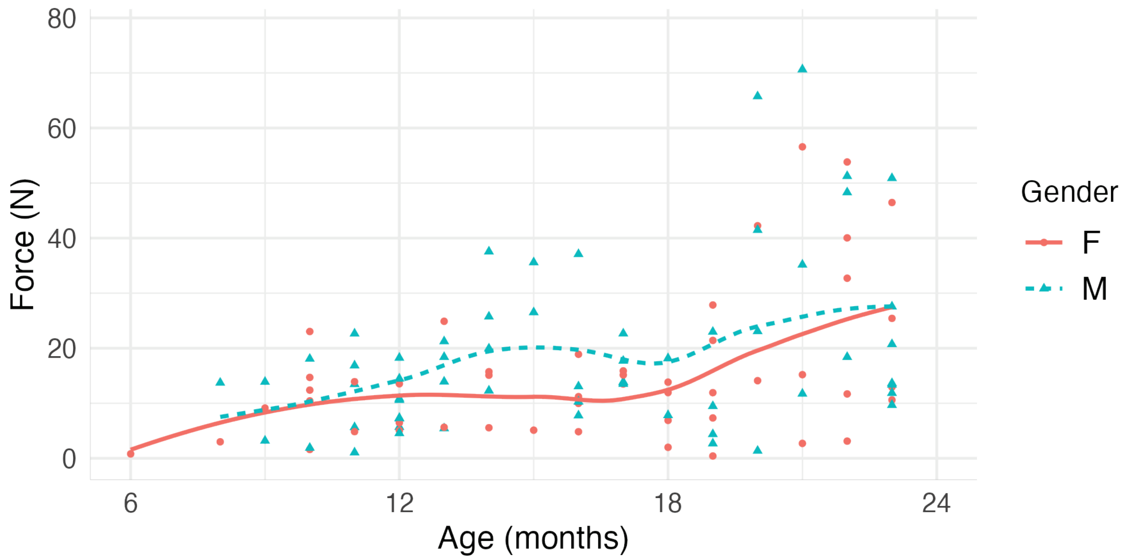
Posture: Pull with one or two hands

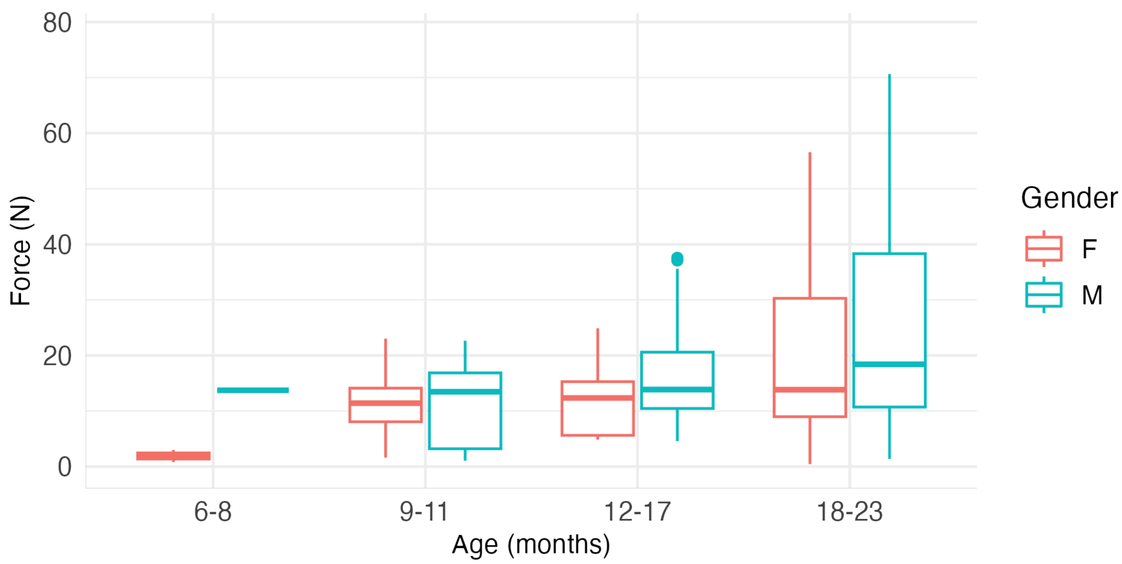
Interface: Bar

Units: Newton



DynamicBar_Pull





DynamicBar_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	1	13.7		13.7	13.7	13.7	13.7	13.7
6-8	0.50-0.74	F	2	1.9	1.5	0.8	0.9	1.9	2.9	3.0
6-8	0.50-0.74	Both	3	5.8	6.9	0.8	1.0	3.0	12.7	13.7
9-11	0.75-0.99	M	9	10.8	7.9	1.1	1.4	13.5	20.8	22.7
9-11	0.75-0.99	F	8	11.3	6.5	1.6	2.7	11.4	20.1	23.0
9-11	0.75-0.99	Both	17	11.0	7.1	1.1	1.5	12.4	22.7	23.0
12-17	1.00-1.49	M	27	16.5	9.4	4.6	5.5	13.9	36.6	37.6
12-17	1.00-1.49	F	16	11.7	5.9	4.8	5.0	12.4	20.4	24.9
12-17	1.00-1.49	Both	43	14.7	8.5	4.6	5.1	13.5	34.7	37.6
18-23	1.50-1.99	M	23	25.2	20.2	1.4	2.9	18.4	64.3	70.6
18-23	1.50-1.99	F	23	20.5	17.0	0.4	2.1	13.8	53.1	56.6
18-23	1.50-1.99	Both	46	22.9	18.6	0.4	2.2	14.7	55.9	70.6

DynamicBar_Push

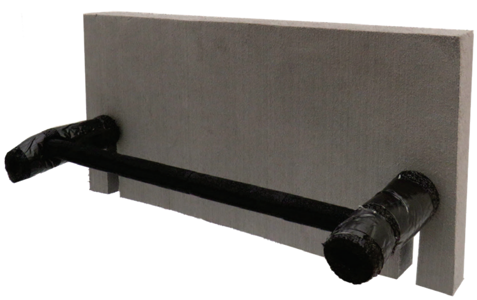
Description: Standing

Configuration: Elbow_Stand

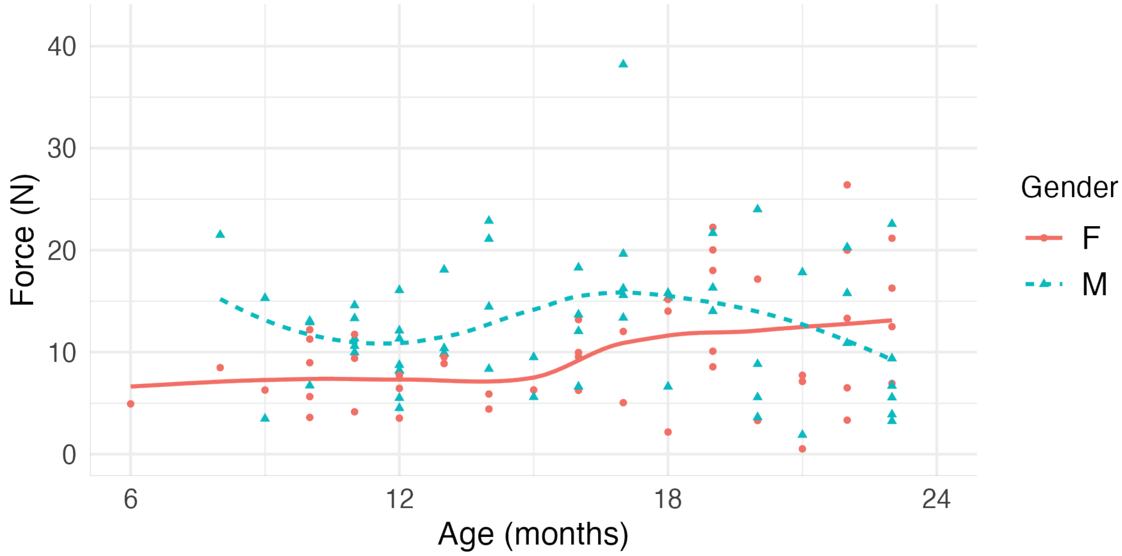
Posture: Push with one or two hands

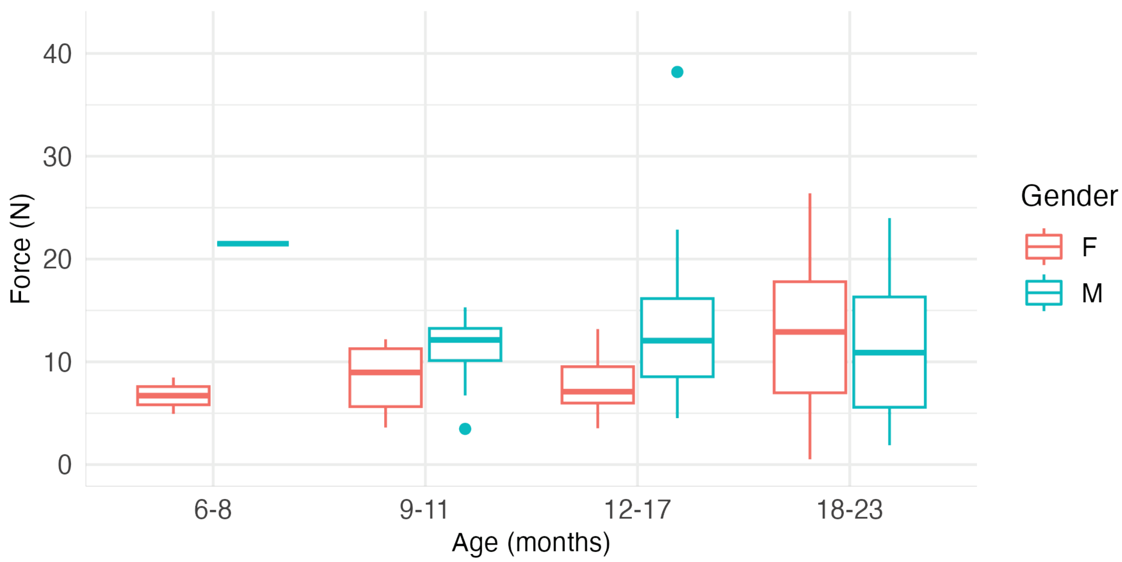
Interface: Bar

Units: Newton



DynamicBar_Push





DynamicBar_Push (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	1	21.5		21.5	21.5	21.5	21.5	21.5
6-8	0.50-0.74	F	2	6.7	2.5	4.9	5.1	6.7	8.3	8.5
6-8	0.50-0.74	Both	3	11.6	8.7	4.9	5.3	8.5	20.2	21.5
9-11	0.75-0.99	M	10	11.1	3.7	3.5	4.9	12.1	15.0	15.3
9-11	0.75-0.99	F	9	8.1	3.3	3.6	3.8	9.0	12.0	12.2
9-11	0.75-0.99	Both	19	9.7	3.7	3.5	3.6	10.6	14.7	15.3
12-17	1.00-1.49	M	27	13.3	7.0	4.5	5.5	12.1	22.3	38.2
12-17	1.00-1.49	F	14	7.8	2.9	3.5	4.1	7.1	12.4	13.2
12-17	1.00-1.49	Both	41	11.4	6.4	3.5	4.5	9.8	21.1	38.2
18-23	1.50-1.99	M	21	11.9	7.0	1.9	3.2	10.9	22.6	24.0
18-23	1.50-1.99	F	22	12.4	7.3	0.5	2.2	12.9	22.2	26.4
18-23	1.50-1.99	Both	43	12.1	7.1	0.5	2.3	12.5	22.5	26.4

Cart_Pull

Description: Standing

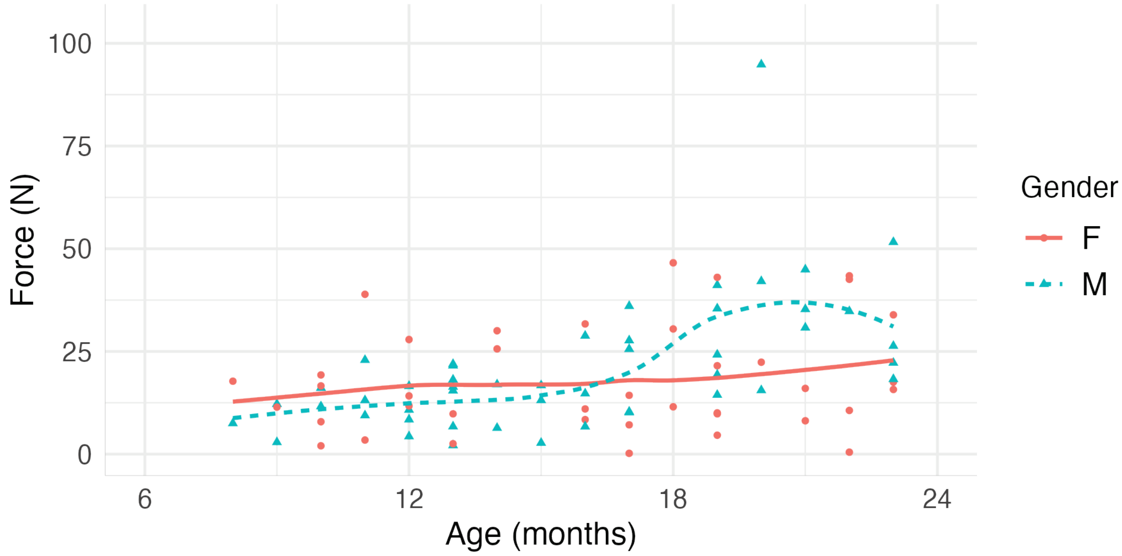
Configuration: Elbow_Stand

Posture: Pull with one or two hands

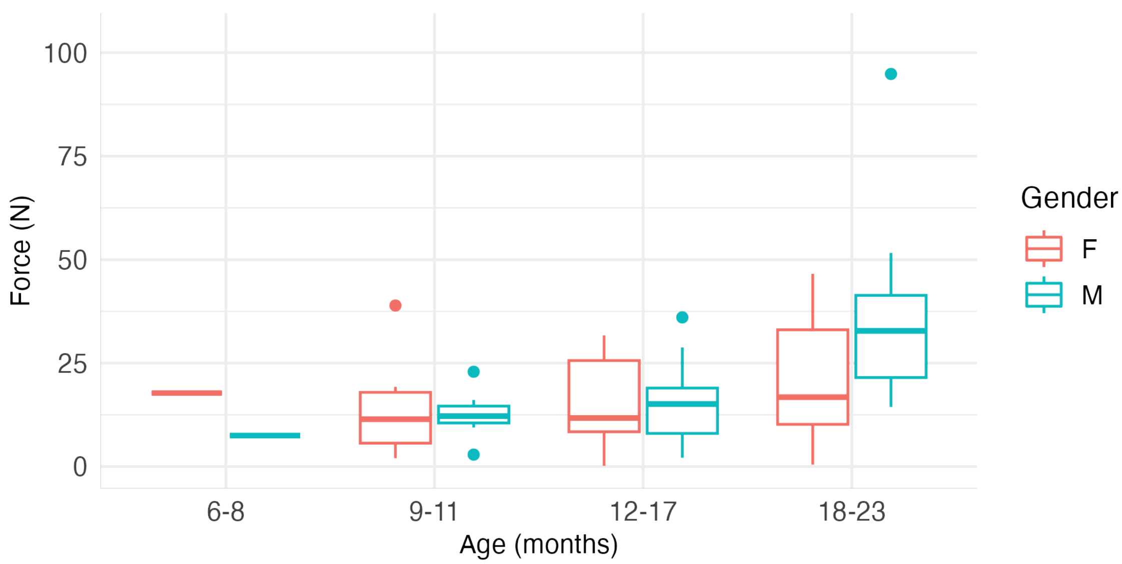
Interface: Cart

Units: Newton

Cart_Pull



Force (N)
100
75
50
25
0
6
12
18
24
Age (months)
Gender
F
M



Force (N)
100
75
50
25
0
6-8
9-11
12-17
18-23
Age (months)
Gender
F
M

Cart_Pull (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	1	7.5		7.5	7.5	7.5	7.5	7.5
6-8	0.50-0.74	F	1	17.8		17.8	17.8	17.8	17.8	17.8
6-8	0.50-0.74	Both	2	12.6	7.3	7.5	8.0	12.6	17.3	17.8
9-11	0.75-0.99	M	7	12.6	6.1	2.9	4.9	12.2	20.9	22.9
9-11	0.75-0.99	F	7	14.2	12.6	2.0	2.5	11.5	33.0	38.9
9-11	0.75-0.99	Both	14	13.4	9.6	2.0	2.6	11.9	28.5	38.9
12-17	1.00-1.49	M	24	14.9	8.8	2.1	3.0	15.1	28.6	36.0
12-17	1.00-1.49	F	13	15.0	10.5	0.2	1.6	11.7	30.7	31.7
12-17	1.00-1.49	Both	37	14.9	9.3	0.2	2.5	14.2	30.4	36.0
18-23	1.50-1.99	M	16	34.5	19.6	14.4	15.3	32.8	62.4	94.8
18-23	1.50-1.99	F	18	21.6	14.8	0.5	4.0	16.8	43.9	46.6
18-23	1.50-1.99	Both	34	27.6	18.1	0.5	6.9	23.3	48.3	94.8

Cart_Push

Description: Standing

Configuration: Elbow_Stand

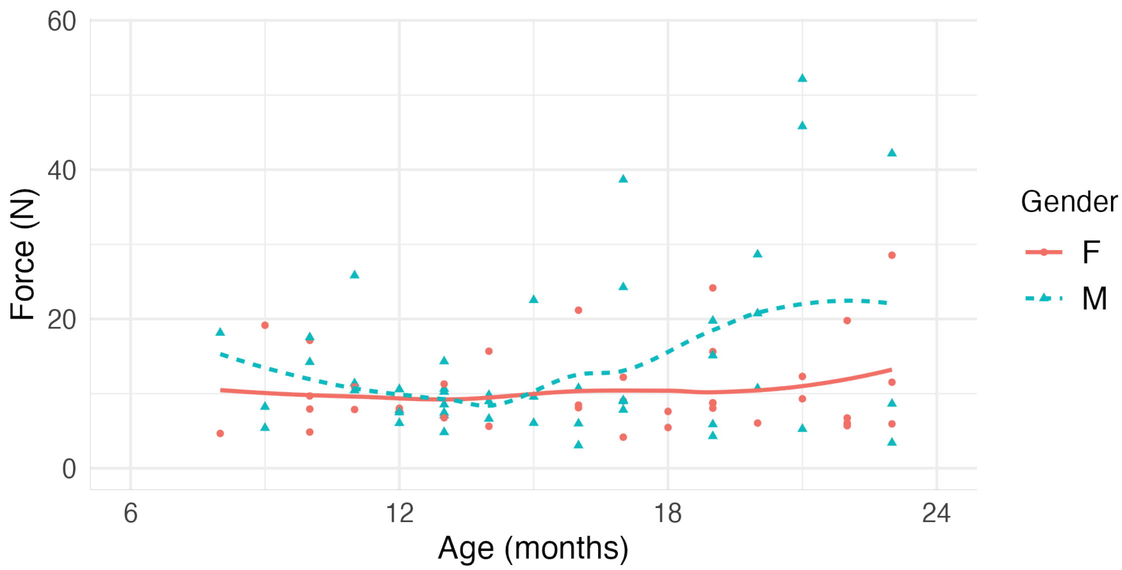
Posture: Push exertion with one or two hands

Interface: Cart

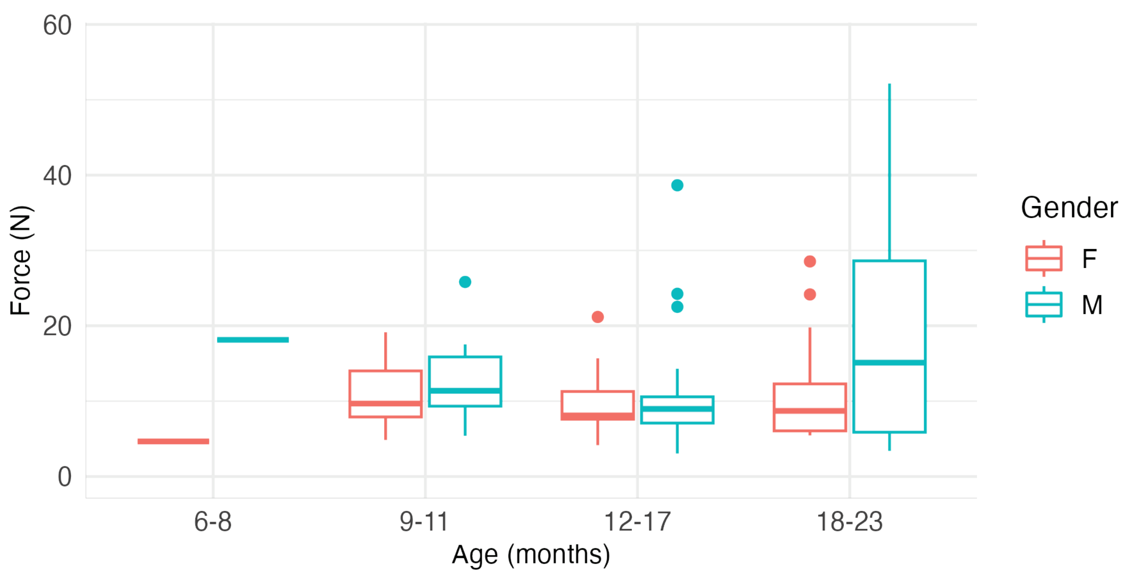
Units: Newton

[No photo available]

Cart_Push



Force (N)
60
40
20
0
6
12
18
24
Age (months)
Gender
F
M



Force (N)
60
40
20
0
6-8
9-11
12-17
18-23
Age (months)
Gender
F
M

Cart_Push (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	1	18.1		18.1	18.1	18.1	18.1	18.1
6-8	0.50-0.74	F	1	4.7		4.7	4.7	4.7	4.7	4.7
6-8	0.50-0.74	Both	2	11.4	9.5	4.7	5.3	11.4	17.5	18.1
9-11	0.75-0.99	M	7	13.3	6.8	5.4	6.2	11.4	23.3	25.8
9-11	0.75-0.99	F	7	11.1	5.2	4.9	5.8	9.7	18.6	19.2
9-11	0.75-0.99	Both	14	12.2	5.9	4.9	5.2	10.7	21.5	25.8
12-17	1.00-1.49	M	25	10.7	7.5	3.1	5.1	9.0	23.9	38.7
12-17	1.00-1.49	F	13	9.7	4.5	4.2	5.0	8.1	17.9	21.2
12-17	1.00-1.49	Both	38	10.3	6.6	3.1	4.7	8.5	22.8	38.7
18-23	1.50-1.99	M	13	20.2	16.9	3.4	3.9	15.1	48.4	52.2
18-23	1.50-1.99	F	17	11.2	6.9	5.5	5.7	8.7	25.0	28.5
18-23	1.50-1.99	Both	30	15.1	12.9	3.4	4.7	9.0	44.2	52.2

2F_Seated_Push

Description: Seated

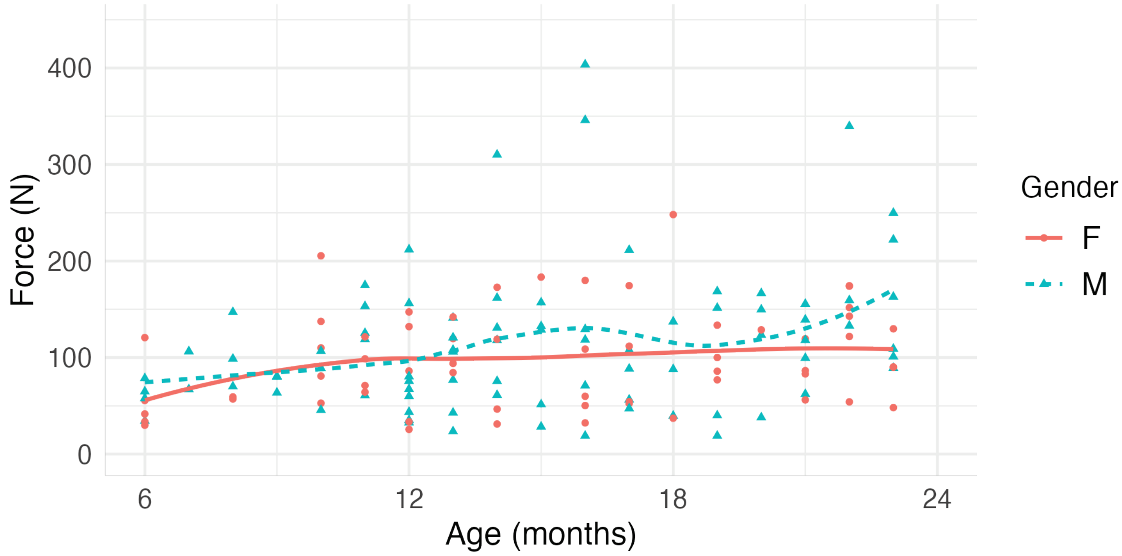
Configuration: 2F_FootBoard_Seated

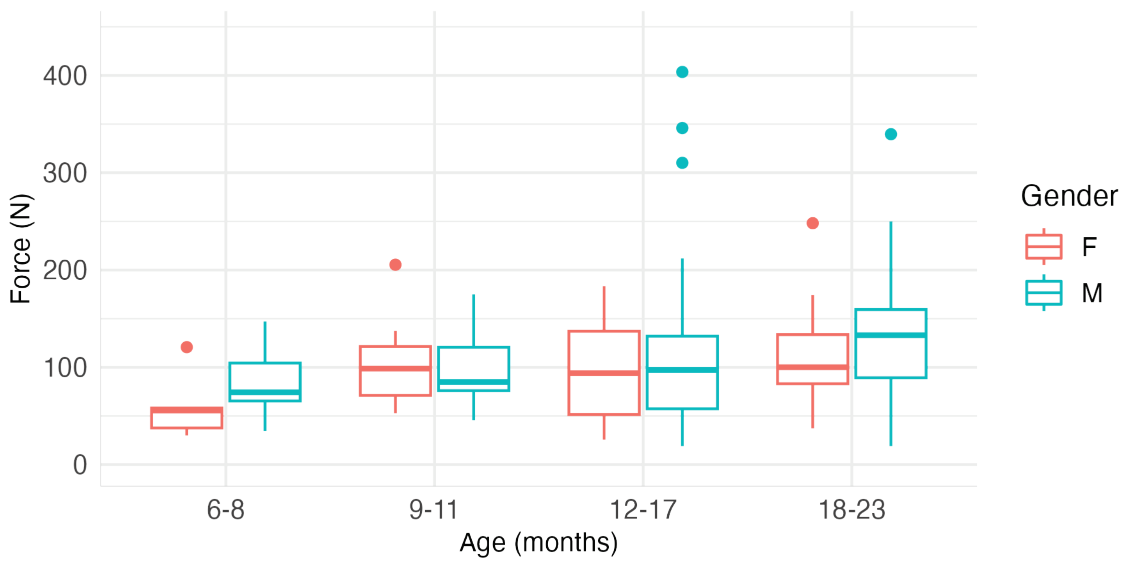
Posture: Two-foot seated push

Interface: FootBoard

Units: Newton

2F_Seated_Push





2F_Seated_Push (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	10	83.2	32.0	34.5	45.0	74.3	128.8	147.1
6-8	0.50-0.74	F	7	56.9	30.5	29.9	31.1	55.6	102.3	120.7
6-8	0.50-0.74	Both	17	72.3	33.2	29.9	32.9	64.9	126.0	147.1
9-11	0.75-0.99	M	12	98.3	38.8	45.7	54.0	84.9	163.0	175.0
9-11	0.75-0.99	F	9	104.7	46.9	52.8	57.4	98.7	178.3	205.5
9-11	0.75-0.99	Both	21	101.1	41.5	45.7	52.8	89.1	175.0	205.5
12-17	1.00-1.49	M	38	114.1	86.7	19.0	27.7	97.3	315.5	403.6
12-17	1.00-1.49	F	23	97.5	52.7	25.7	31.3	94.0	179.4	183.4
12-17	1.00-1.49	Both	61	107.9	75.6	19.0	28.4	94.0	211.9	403.6
18-23	1.50-1.99	M	25	130.5	70.9	19.0	38.4	133.0	244.3	339.6
18-23	1.50-1.99	F	21	111.1	50.3	37.2	48.2	100.1	174.4	248.1
18-23	1.50-1.99	Both	46	121.7	62.5	19.0	38.4	120.7	241.7	339.6

2F_Supine_Push

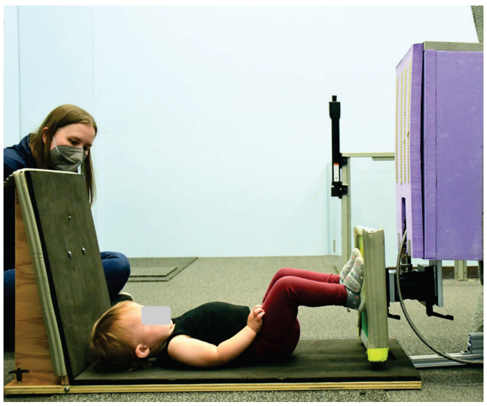
Description: Supine

Configuration: 2F_FootBoard_Supine

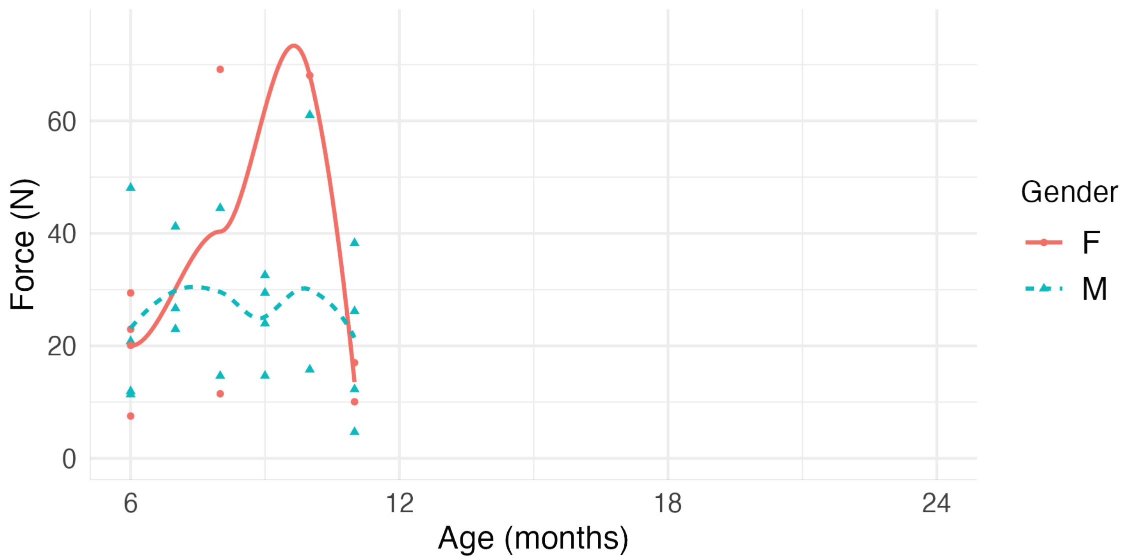
Posture: Two-foot supine push

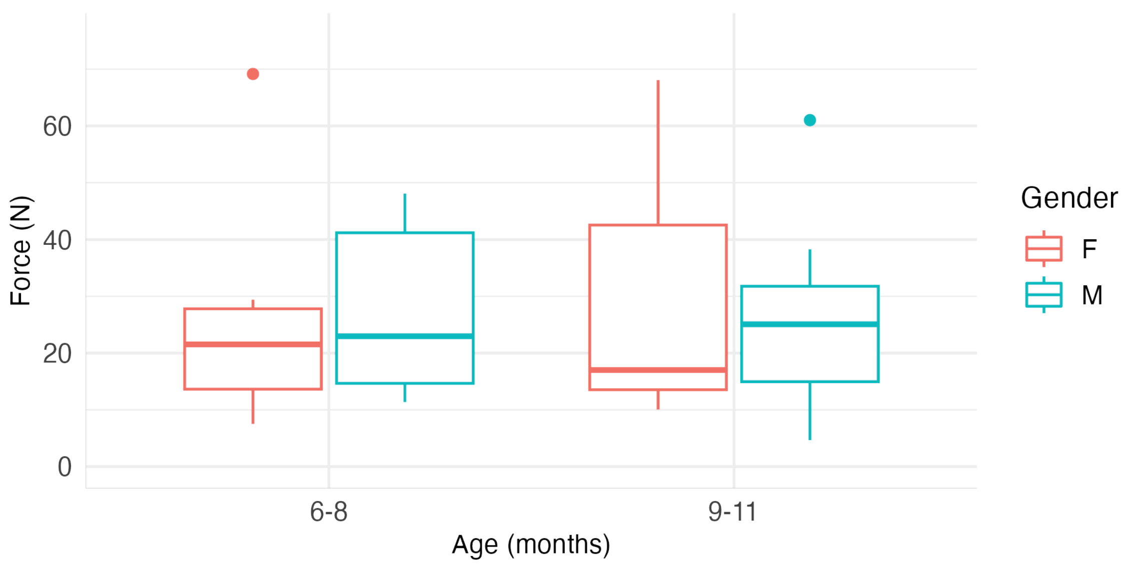
Interface: FootBoard

Units: Newton



2F_Supine_Push





2F_Supine_Push (N)

Age Group (months)	Age Group (years)	Gender	N	mean	sd	min	Q.05	Q.50	Q.95	max
6-8	0.50-0.74	M	9	26.9	14.3	11.4	11.6	23.0	46.7	48.1
6-8	0.50-0.74	F	6	26.8	22.2	7.5	8.5	21.5	59.2	69.2
6-8	0.50-0.74	Both	15	26.9	17.1	7.5	10.2	23.0	54.4	69.2
9-11	0.75-0.99	M	10	25.9	16.0	4.7	8.1	25.1	50.8	61.0
9-11	0.75-0.99	F	3	31.7	31.7	10.1	10.8	17.0	63.0	68.1
9-11	0.75-0.99	Both	13	27.2	19.1	4.7	7.9	24.0	63.9	68.1
12-17	1.00-1.49	M	0							
12-17	1.00-1.49	F	0							
12-17	1.00-1.49	Both	0							
18-23	1.50-1.99	M	0							
18-23	1.50-1.99	F	0							
18-23	1.50-1.99	Both	0							