Behavior Analysis Of Catching Using 3D Pose Estimation

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DEDICATION

To my Parents and sister, who supported me through this journey 10000 kilometers away.

ABSTRACT

Catching, a complex and fundamental prehension task, is crucial for daily life yet remains understudied despite its implications for robotics, rehabilitation, and neuroprosthetics. This thesis investigates the intricate sensorimotor coordination involved in human catching, building upon theories like the Dual Visuomotor Channel (DVC) and Multiple Motor Channel (MMC) to understand how the brain orchestrates dynamic hand movements.

Ten right-handed participants engaged in externally thrown, self-thrown, and visually guided "pretend" catches using four ball sizes. Behavior was recorded with three GoPro cameras, and 3D pose estimation was performed via FreeMocap (Matthis & Cherian, 2022), leveraging MediaPipe (Zhang et al., 2020) for 2D analysis and triangulation for 3D reconstruction. Three primary kinematic metrics were quantified: 1) Euclidean distance between the thumb tip and other fingertips (opposable distance); 2) Perpendicular distance from each fingertip to the palm plane (prehensile distance); and 3) The hand's rotation angle in the X-Z plane, derived from the palm's normal vector.

Results revealed Maximum Pregrasp Aperture (MPA) scaled linearly with ball diameter, indicating anticipatory hand shaping. Distinct grasping strategies emerged for different ball sizes: larger balls elicited "precision catches" characterized by significant finger splay and thumb-pinky opposition, while smaller balls often resulted in "power catches" with minimal thumb involvement and greater finger flexion into the palm. Self-catches further highlighted the interplay of anticipatory and feedback control. These findings enhance understanding of human prehension, providing quantitative data valuable for advancing motor control models, developing adaptive robotic systems, and improving human-machine interfaces.

ACKNOWLEDGEMENTS

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ETHICS STATEMENT

Work described in this thesis received research ethics approval from the University of Alberta Research Ethics Board, Project Name “Reach and finger movements used for catching”, No. 00146038, October 1, 2024.

USE OF AI

Throughout the preparation of this thesis, artificial intelligence (AI) tools were utilized to enhance the quality, clarity, and consistency of the writing. Specifically, ChatGPT 3.5 and Claude Sonnet 4 were employed for the following purposes:

Grammar and Spell Checking: AI-powered writing assistants helped identify and correct grammatical errors, punctuation mistakes, and spelling inconsistencies, ensuring adherence to academic English standards.

Clarity and Conciseness: These tools provided suggestions for rephrasing sentences, simplifying complex structures, and improving overall readability, which contributed to a more precise and impactful presentation of ideas.

Consistency Checks: AI algorithms assist in maintaining consistent terminology and formatting throughout the document, particularly in areas requiring specific academic conventions.

It is important to state that AI tools were used solely as aids for refining the language and presentation of this thesis. They did not generate any core ideas, conduct any primary research, perform data analysis (beyond potentially offering initial visualization of ideas within data software), or formulate any conclusions or results. All intellectual content, experimental design, data interpretation, and critical analysis presented herein are the original work of the author. The author maintains full responsibility for the content, accuracy, and originality of this thesis.

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Introduction

Reaching out with one hand to grasp a cup of coffee, stopping a rolling ball, or catching a thrown object are all common everyday movements. This versatile ability to adapt prehension to complex spatial and perceptual challenges develops early in life (Vonhofsten, 1983). Nevertheless, moving the hand accurately to the target and grasping it requires processing spatial and perceptual properties that can vary significantly between different targets (Alderson et al., 1974).

In this thesis, *catching* refers to the anticipatory interception of a moving object using the hand, typically involving real-time visual tracking, motor prediction, and precise temporal coordination.

Among the wide range of manual actions, catching stands out as a particularly complex and dynamic form of prehension. Unlike reaching for a static object, catching demands real-time prediction of a moving target's trajectory, precise timing, and rapid sensorimotor coordination (Zago et al., 2008; Cesqui et al., 2012). These requirements place unique constraints on visuomotor processing, setting catching apart from more conventional grasping tasks. The need to anticipate the spatiotemporal evolution of the object—often under conditions of uncertainty or brief occlusion—highlights the critical role of feedforward mechanisms alongside visual feedback (Tresilian, 1995). Despite its complexity and everyday relevance, catching remains relatively understudied in the literature on prehension, with few studies systematically exploring how the sensorimotor system adapts to moving targets. Furthermore, successful catching relies on the fine-tuned coordination of reaching and grasping components, making it an ideal behavior through which to examine the integration of perceptual and motor systems in naturalistic, time-sensitive contexts.

Motivation and Real-World Importance

Understanding the intricacies of catching is not merely an academic exercise—it has significant implications for a range of practical applications. Catching is a complex motor skill that requires rapid sensorimotor integration, real-time prediction of an object's trajectory, and precise coordination. Studies of catching provide a valuable model for investigating how the human brain orchestrates movements under dynamic and uncertain conditions (Zago et al., 2004; Tresilian, 1995). By examining how the sensorimotor system adjusts to moving targets, researchers can gain insights into the neural and biomechanical principles that support efficient motor control.

The importance of understanding catching spans several fields:

Sports Performance: In sports such as baseball, cricket, and volleyball, accurately intercepting moving objects is critical for success. Research on anticipation and sensorimotor timing underscores how expert athletes adjust their movements in real time to match the dynamic nature of play (Abernethy & Neal, 1999; Williams & Hodges, 2005). Enhancing these predictive skills not only improves performance but also helps reduce injury risk by fostering better movement coordination.

Robotics and Artificial Intelligence: Replicating human catching in robotic systems is a long-standing challenge in the field of robotics. Insights drawn from human motor control are essential for designing robotic manipulators that can adapt to unpredictable environments and interact safely with humans (Bicchi & Kumar, 2000; Mussa-Ivaldi & Solla, 2003). Such work contributes to advances in both industrial automation and assistive technologies.

Rehabilitation and Neuroprosthetics: For individuals recovering from neurological injuries or degenerative conditions, disruptions in coordinated movement are common. A better understanding of the mechanisms underlying motor tasks, such as catching, could inform the development of targeted rehabilitation strategies and neuroprosthetic devices aimed at restoring motor function. This aligns with the framework proposed by Bernhardt et al. (2017), which emphasizes interventions prioritizing neural repair and behavioral restitution over compensatory strategies to achieve true recovery of pre-stroke motor patterns.

Human–Machine Interaction: With the growing integration of wearable technologies and interactive devices in daily life, optimizing the interface between human motion and machine response is critical. Research on sensorimotor integration and predictive control in dynamic tasks, such as catching, provides a framework for developing systems that anticipate and adapt to rapid human movements. For instance, studies in adaptive robotics demonstrate how biological principles of motor coordination can enhance the safety and responsiveness of collaborative machines (Ajoudani et al., 2018)

Dual Visuomotor Channel Theory

The Dual Visuomotor Channel (DVC) theory (also referred to as Jeannerod theory) suggests that the perceptual and spatial properties of target objects are managed by two distinct visuomotor channels (Arbib, 1981; Jeannerod 1981; Haggard & Wing, 1997; Jeannerod, 1999). A reach channel generates the movement of the hand to the target's location based on its extrinsic properties (position, orientation), while a grasp channel shapes the hand and fingers to grasp the target based on its intrinsic properties (size, shape). The integration of these two movements occurs under foveal vision, with the gaze anchored on the target from the point of reach initiation until the moment of grasping (Prablanc et al., 1979; Neggers & Bekkering, 2000; de Bruin et al., 2008; Sacrey et al., 2012; Kuntz et al., 2018).

Support for the DVC theory comes from various lines of behavioral research. The two movements can be dissociated by movement perturbation (Gentilucci et al., 1992; Hoff & Arbib, 1993) and by having participants reach without vision or into peripheral vision (Karl et al., 2012; Hall et al., 2014). During development, the reach matures earlier than the grasp (Karl & Whishaw, 2014; Thomas et al., 2014). Functional magnetic resonance imaging (fMRI), transcranial magnetic stimulation (TMS), and brain injury studies further support the idea that the reach and grasp are mediated by different pathways from visual to parieto-frontal cortex pathways (Jeannerod et al., 1994; Binkofski et al., 1998; Culham & Valyear 2006; Cavina-Pratesi et al., 2010a; Cavina-Pratesi et al., 2010b; Vesia et al., 2013; Whishaw et al., 2016; Cavina-Pratesi et al., 2018).

The reach is supported by a visual pathway to the frontal cortex through the superior parieto-occipital cortex (SPOC, V6A) and medial intraparietal sulcus (MIP) of the parietal cortex, whereas the grasp is supported by a visual pathway to the frontal cortex through the anterior intraparietal sulcus (AIP) of the parietal cortex (Galletti et al., 2003).

Some of key supports for DVC includes:

Neuropsychological Studies: Patients with specific brain lesions have shown dissociations in their abilities to perceive and act. For instance, individuals with damage to the ventral stream may struggle to recognize objects but can still reach for them accurately, supporting the idea of separate processing streams for perception and action (James et al., 2003).

Evolutionary Evidence: manual prehension consists of two temporally integrated movements, each supported by distinct visuomotor pathways in the occipito-parieto-frontal cortex. The reach is mediated by a dorsomedial pathway, while the grasp is associated with a different pathway. (Karl and Whishaw, 2013)

Smeets and Brenner's Theory

A work by Smeets and Brenner. (1999), has challenged this channel theory perspective, and criticize it in three points:

1. **Intrinsic and Extrinsic Properties are Not Independent:** According to Jeannerod, extrinsic properties (like the object's position and orientation) guide hand transport, while intrinsic properties (like size and shape) influence grip size. However, Smeets and Brenner argue that **grip size depends on both intrinsic and extrinsic properties**, not just intrinsic ones. For example, if an object's orientation changes, this can affect the grip size and hand position, suggesting these components are interdependent.
2. **Anatomical Arguments**: Jeannerod's theory aligns the transport and grip components with distinct anatomical structures. Proximal muscles control hand transport, and distal muscles control the grip. Smeets and Brenner challenge this distinction by pointing out that the control of muscles is not as clear-cut. Distal and proximal muscles work together in both transport and grip, and thus the separation between them in Jeannerod's model is anatomically unjustified.

3. **Inflexibility in Modeling**: Jeannerod's model has not inspired much in terms of computational modeling. The only model that exists, by Hoff & Arbib (1993), is heavily dependent on experimentally observed parameters and doesn't offer deep explanatory power. It incorporates additional controllers for grip and transport without explaining the relationships between variables.

Smeets and Brenner (1999) propose an alternative view, challenging this idea of two independent visuomotor channels for transport and grasp. Instead, they suggest that grasping can be understood as a form of independent movement of the thumb and fingers, with both digits moving towards specific positions on the object's surface. This model eliminates the need for separate “reach” and “grasp” components. They argue that grasping is essentially pointing with the thumb and fingers, coordinated by a minimum jerk model to achieve smooth and efficient movement. Furthermore, Smeets and Brenner propose that the thumb and fingers approach the object perpendicularly, ensuring accuracy and stability. Their model integrates transport and grip into a single framework, offering a more flexible and generalizable explanation of grasping without the anatomical and functional divisions suggested by the Dual Visuomotor Channel theory. This approach also aligns more closely with experimental observations of how object size, speed, and task demand influence grasping behavior.

Recent research, including the work of Rouse and Schieber (2018), also raises the question of how separate the processes of reaching and grasping truly are. Rouse and colleagues challenge the traditional view of distinct neural pathways for these actions, suggesting a more integrated model of motor control. By analyzing neural activity in the primary motor cortex during reach-to-grasp tasks, they discovered patterns that point to a closer interaction between the two processes. These findings not only enhance our understanding of motor control but also have important implications for developing neuroprosthetic devices and rehabilitation techniques for individuals with motor impairments. Furthermore, these insights extend to fields such as robotics, where they can help in designing systems that more naturally replicate human dexterity.

Multiple Motor Channel (MMC) Theory

Building on the Dual Visuomotor Channel (DVC) model, the **Multiple Motor Channel (MMC) theory**, as proposed by Karl and Whishaw (Karl & Whishaw, 2013; Whishaw & Karl, 2014), provides a comprehensive framework for understanding the neurobehavioral control of skilled hand movements. Unlike the DVC model, which emphasizes the distinction between reaching and grasping, MMC theory posits that hand movements are governed by three distinct motor channels: **reach**, **grasp**, and **withdraw**. Each channel operates through separate neural pathways, sensory control mechanisms, and evolutionary origins (Sacrey & Whishaw, 2012).

1. Neural Basis and Pathways

MMC theory proposes that each movement component is controlled by distinct neural circuits (Sacrey & Whishaw, 2012; Karl & Whishaw, 2013):

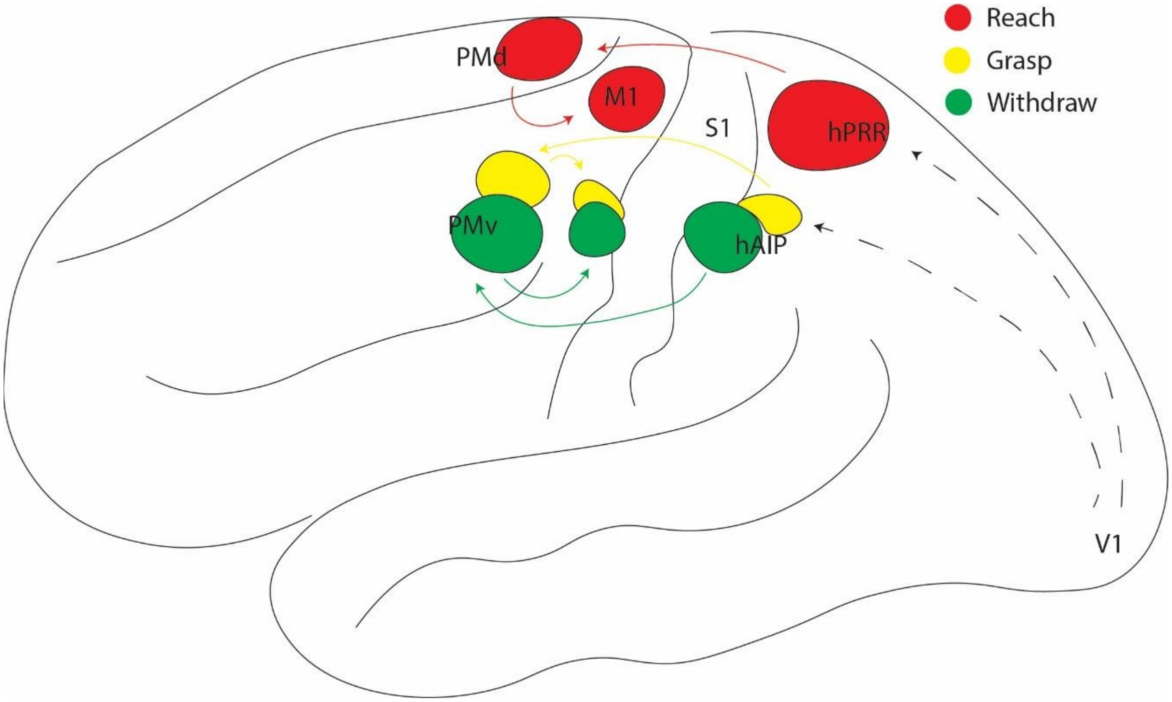


Figure 1. Brain pathways for grasping. Proposed reach (medium gray), grasp (dark gray), and withdraw (light gray) pathways from parietal to premotor to motor cortex. Also illustrated are inputs from the cortical visual system. (dotted lines). Notes: PMd = dorsal premotor cortex, PMv = ventral premotor cortex, M1 = primary motor cortex, S1 = primary somatosensory cortex, hPRR = human parietal reach region, hAIP = human intraparietal sulcus, V1 = primary visual cortex. (Adapted from Corbetta & Santello, 2018)

- **Reach**: Governed by dorsal motor circuits in the parietofrontal network, including the human parietal reach region (hPRR) and dorsal premotor cortex (PMd). These circuits evolved from forelimb stepping movements in early mammals and guide the hand toward an object's spatial location.

- **Grasp**: Managed by ventrolateral circuits involving the anterior intraparietal sulcus (hAIP) and ventral premotor cortex (PMv). These pathways originated from manipulatory feeding behaviors.

- **Withdraw**: Relies on somatosensory feedback from the hand and mouth, mediated by parietal-to-motor cortical pathways. This circuit lacks visual input and evolved for hand-to-mouth feeding actions.

Brain imaging studies (e.g., fMRI and TMS) confirm these dissociable pathways. For instance, the reach pathway activates the superior parieto-occipital cortex (SPOC) and medial intraparietal sulcus (MIP), while the grasp pathway engages the hAIP and PMv (Culham & Valyear, 2006; Filimon et al., 2009).

2. Developmental Trajectory

MMC theory emphasizes that skilled hand movements emerge through developmental stages:

- **Precursor Movements**: Newborns exhibit semi-spontaneous **pre-reach**, **pre-grasp**, and **pre-withdraw** actions. For example, neonates perform hand-to-mouth movements linked to feeding satisfaction (Rochat et al., 1988), while self-touching behaviors (e.g., palmar contact with the torso) refine proprioceptive body maps (Thomas et al., 2015).

- **Integration (4–6 months)**: Infants begin coordinating reach, grasp, and withdraw into functional sequences (e.g., bringing objects to the mouth). However, these movements rely on somatosensory feedback, resembling unsighted adults' dissociated reach-then-grasp actions (Karl & Whishaw, 2014; Vonhofsten, 1983).

- **Visual Refinement (9–12 months)**: Feedforward visual control emerges, enabling hand preshaping during reaches (Corbetta et al., 2012). By 12 months, reach trajectories smooth, but grasp closure remains delayed compared to adults (von Hofsten & Rönnqvist, 1988). Full maturation of visual-motor integration extends into early childhood (Kuhtz-Buschbeck et al., 1998).

3. Evolutionary Perspective

Each MMC component evolved to address distinct survival challenges:

- **Reach**: Originated from locomotor circuits for forelimb stepping in early mammals, later co-opted for visually guided ballistic reaches (Karl & Whishaw, 2013).
- **Grasp**: Rooted in manipulatory feeding behaviors, refined through primate evolution for object handling (Whishaw, 2003).
- **Withdraw**: Derived from primitive hand-to-mouth feeding actions, retained across species (Sacrey & Whishaw, 2012).

Primate evolution integrated these circuits with cortical visual systems, enabling precise visuomotor coordination (Kaas & Stepniewska, 2016). Subcortical visual pathways initially drove whole-body orienting (e.g., mouth capture), while cortical expansions allowed advanced hand preshaping (Karl et al., 2012).

4. Sensory and Motor Integration

- **Somatosensory Dominance**: Early movements depend on tactile and proprioceptive feedback. Infants learn hand shaping through haptic exploration (e.g., “sticky mittens” experiments; Libertus & Needham, 2010). Adults retain this flexibility, dissociating movements without vision (Hall et al., 2014).

- **Visual Streamlining**: In sighted adults, vision integrates reach and grasp into fluid actions. Visual occlusion reverts control to somatosensory guidance, highlighting the system’s adaptability (Karl et al., 2012).

5. Broader Implications

- **Autism Spectrum Disorder (ASD)**: Children with ASD exhibit disrupted integration of reach, grasp, and withdraw. Abnormal somatosensory connectivity (Thompson et al., 2017) and dorsal stream hypoconnectivity (Villalobos et al., 2005) impair motor coordination (Mari et al., 2003).

- **Robotics and Neuroprosthetics**: MMC-inspired models improve robotic limb design by mimicking modular motor control (Yamada et al., 2013).

Napier’s Theory on Hand Grip

Another theory in hand grips and grasps is J.R. Napier theory (1956). Napier, a prominent figure in the study of human anatomy and evolution, introduced a classification system for hand grips that has significantly influenced our understanding of prehensile movements. His theory primarily identifies two main types of grips:

Figure 2. Power Grip.

Power grip involves the fingers flexing to hold an object against the palm, with the thumb adducted. It is typically used for tasks requiring strength, such as holding a hammer or lifting heavy objects.

Figure 3. Precision Grip.

In contrast, the precision grip allows for finer manipulation of objects, where the object is held away from the palm, often between the thumb and one or more fingers. This grip is essential for tasks that require dexterity, such as writing or picking up small items.

Napier's classification also includes other grip types, such as hook and scissor grips, which further elaborate on the functional capabilities of the human hand. His work laid the foundation for subsequent studies in biological anthropology and ergonomics. His theory also emphasizes the evolutionary adaptations of the human hand for various tasks such as throwing and tool use. One study calls the precision grip, throwing grip, and the power grip, clubbing grip, showing this adaptation in hand evolution (Young 2003). This theory is also applicable to studies on primate hands morphology and what is their specific usage of these hand grips (Preuschoft 2019).

However, while ground-breaking, Napier's theory on hand grips has faced several limitations and criticisms over the years. One of the primary criticisms of Napier's theory is that it oversimplifies the complexity of human hand grips. While Napier's classification of power grip and precision grip provided a foundational framework, subsequent research has shown that hand grips exist on a continuum rather than in discrete categories. This realization has led to more nuanced classifications and studies of hand function (Liu et al, 2021). Also, Napier's theory primarily focused on static grip positions. However, hand function often involves dynamic movements and transitions between different grip types. This limitation has led to research focusing on the dynamic aspects of hand movements and how grip types change during complex tasks.

Catching In animals

Catching is not a skill unique to humans. Dogs, for example, catch frisbees using their mouths rather than hands, but the underlying navigation process is quite like that of humans (Shaffer et al., 2004). Interestingly, felines also play catch (Forman et al., 2023). However, catching for animals is not just a game; in many cases, it is essential for survival. For instance, barn owls perform complex calculations to navigate and catch prey in the dark using only the sound of their target (Takahashi, 2010). Similarly, primates display diverse grasping strategies that reflect their evolutionary adaptations to different tasks. Studies reveal that great apes use precision grips to catch small objects like bugs and power grips for larger objects like fruits, with these behaviors shaped by object size and task demands (Pouydebat et al., 2009). Further, the "Multiple Motor Channel Theory" suggests that hand movements in animals, including catching and grasping, have evolved as distinct motor actions—such as reach, grasp, and withdraw—driven by both neural and ecological factors (Whishaw & Karl, 2019). These findings highlight how the evolution of catching skills intertwines with feeding strategies and motor control across species.

Theory:

The **Dual Visuomotor Channel (DVC) theory** (Jeannerod, 1981) proposes that reaching and grasping are controlled by two separate systems. The *reach* is guided by extrinsic object features like location and orientation, while the *grasp* is shaped by intrinsic features like size and shape. These components follow different neural pathways: reach involves the dorsomedial parietal areas (e.g., SPOC, MIP), and grasp involves the lateral pathway, particularly the anterior intraparietal sulcus (AIP). Research in development, neuroimaging, and lesion studies supports this separation, showing that reaching and grasping can be independently affected and develop at different rates.

In contrast, **Smeets and Brenner (1999)** argue that grasping does not require separate reach and grasp systems. Instead, they suggest the hand's digits—including the thumb—move independently toward specific contact points on the object. Both intrinsic and extrinsic object properties influence all digit movements. This model treats grasping as coordinated positioning of fingers and thumb, rather than two distinct motor processes. Their theory offers a single, unified explanation of grasping, without relying on anatomical or functional separation.

Hypothesis:

Catching trials with varying throws and ball sizes, using kinetic data, will show whether hand movements follow a two-phase pattern (supporting DVC), or if each digit—including the thumb—moves independently toward object-specific contact points (supporting Smeets and Brenner). I expect the variability in throws and object sizes to help reveal which model better fits real-world catching behavior.

Methods

Participants

A sample size of 10 right-handed participants was chosen based on prior kinematic studies demonstrating that repeated measures design with homogeneous groups (e.g., Karl et al., 2012a; von Hofsten, 1991) can detect significant differences in hand movement parameters. This sample size aligns with feasibility constraints for high-resolution motion capture analysis and ethical considerations, while maintaining rigor for exploratory comparisons between externally thrown, self-thrown, and visually guided catching tasks. Participants were offered snacks for their participation, and they gave informed consent, self-reported as having no history of neurological, sensory, or motor disorders, as well as having normal or corrected-to-normal visual acuity.

Apparatus

Participants were seated in an armless chair with their feet square and placed firmly on the floor. And their hand on their lap. The room was well illuminated, and distractions were removed. Three tasks were presented: 1. catch a ball when it was thrown at them 2. throw a ball upwards and catch it themselves.

In all two tasks participants used targets (spherical balls) of four different sizes, (very small, XS, 2.5 cm in diameter; small, S, 3.5cm in diameter; medium, M, 6cm in diameters; large, L, 9cm in diameter). The size of the targets was selected based on preliminary experiments which showed that participants could accurately differentiate these target sizes.

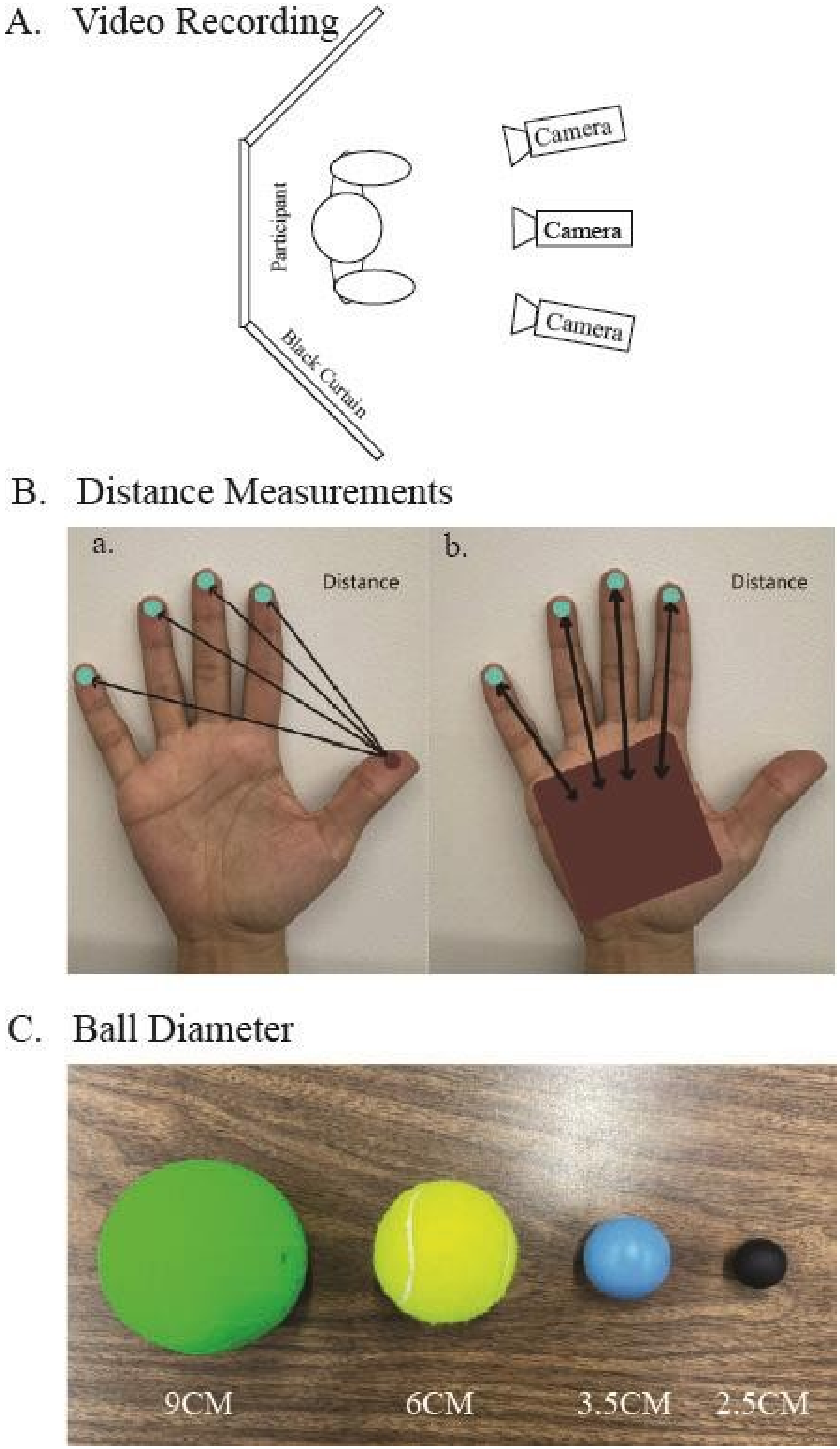

A. Video Recording
Participant
Black Curtain
Camera
Camera
Camera
B. Distance Measurements
a.
Distance
b.
Distance
C. Ball Diameter
9CM
6CM
3.5CM
2.5CM

Figure 4. Experimental method. **A.** Behavior was recorded using three cameras while the participant was seated in front of a black curtain. **B.** From the processed video, two measures were obtained: opposable distance, which is the distance between the thumb pad and the pads of the four fingers, and prehensile distance, which is the distance between the terminal pads of each digit and the palm. **C.** Balls of four different sizes (2.5 cm, 3.5 cm, 6.0 cm [tennis ball], and 9.0 cm) were thrown to the participants so they could perform an overhead catch.

Ba. Distance Between Thumb Fingertip and Other Fingertips

This metric quantifies the Euclidean distance between the thumb tip and the tips of the index, middle, ring, and pinky fingers. These distances reflect hand configuration during motion.

Mathematical Formulation:

Let T_{tip} denote the 3D coordinates of the thumb tip, and F_{tip}^{i} represent the 3D coordinates of the *i*-th fingertip, where *i* ∈ {index, middle, ring, pinky}. The distance d_i is computed as:

$$\boldsymbol{d_i} = \left|\left|\boldsymbol{T_{tip}} - \boldsymbol{F_{tip}^{i}}\right|\right| = \sqrt{(\boldsymbol{T_x} - \boldsymbol{F_x^i})^2 + \left(\boldsymbol{T_y} - \boldsymbol{F_y^i}\right)^2 + (\boldsymbol{T_z} - \boldsymbol{F_z^i})^2}$$

Variables:

- T_{tip}= **(**T_x, T_y, T_z**):** Thumb tip coordinates**.**
- F_{tip}^{i}= **(**F_x^i ,F_y^i ,F_z^i**):** Coordinates of the i-th fingertip.
- $\boldsymbol{d_i}$**:** Distance between thumb tip and finger i (output in mm)

Bb. Distance of Fingertips to the Palm Plane

This metric measures the perpendicular distance from each fingertip to the palm plane. The plane is defined using three anatomical landmarks:

1. Index finger MCP (metacarpophalangeal joint) root (I_{mcp}).
2. Pinky finger MCP root (P_{mcp}).
3. Wrist center (W).

Plane Definition: The plane equation $\boldsymbol{ax} + \boldsymbol{by} + \boldsymbol{cz} + \boldsymbol{d} = 0$ is derived from the three points I_{mcp}, P_{mcp}, and W:

1. Compute two vectors in the plane:

$$\overrightarrow{v_1} = P_{mcp} - I_{mcp} \qquad \overrightarrow{v_2} = W - \boldsymbol{I_{mcp}}$$

2. The normal vector $\vec{n}$ to the plane is:

$$\vec{n} = \overrightarrow{v_1} \times \overrightarrow{v_2} = (a, b, c)$$

3. Solve for d using I_{mcp}:

$$d = -\left(a \cdot I_x + b \cdot I_y + c \cdot I_z\right)$$

Distance Calculation: The perpendicular distance D_j from a fingertip F_{tip}^{j} (where $j \in \{thumb,\ index,\ middle,\ ring,\ pinky\}$) to the plane is:

$$D_j = \frac{|a \cdot F_x^j + b \cdot F_y^j + c \cdot F_z^j + d|}{\sqrt{a^2 + b^2 + c^2}}$$

Variables:

- $\boldsymbol{\vec{n}} = (\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c})$**: Plane's normal vector.**

- **F_{tip}^{i}: 3D coordinates of the $j-th$ fingertip.**
- **D_j:** Perpendicular distance to the palm plane (output in mm).

Implementation Notes

1. Landmarks: All points (fingertips, MCP joints, wrist) are obtained from the 3D pose estimation model.
2. Plane Validity: The plane is uniquely defined by I_{mcp}, P_{mcp} and W (non-collinear points).

Contextual Purpose

- Method A: Characterizes thumb opposition, for finding opposable distance.
- Method B: Quantifies finger flexion/extension by measuring fingertip displacement relative to the palm.

Angle Calculation in the X-Z Plane

This metric quantifies the hand's rotation from a top-down perspective by calculating the angle of the palm's normal vector within the X-Z plane. This angle provides insight into clockwise versus counterclockwise hand rotations.

For that we need the palm normal vector which is calculated as so:

$$\vec{n} = \frac{\overrightarrow{n_{\text{unnormalized}}}}{||\overrightarrow{n_{\text{unnormalized}}}||} = (N_x, N_y, N_z)$$

Angle Calculation:

The angle θ of the unit palm normal vector in the X-Z plane is calculated using the $arctan2$ function, which takes the Z-component (N_z) and X-component (N_x) of the normal vector as arguments. This function correctly determines the angle across all four quadrants, returning a value in radians within the range $(-\pi, \pi]$ (i.e., $(-180°, 180°]$).

$$\theta = \mathrm{arctan2}(N_z, N_x)$$

In this formulation, an angle of 0 radians corresponds to the palm normal pointing along the positive X-axis. Positive angles indicate a counter-clockwise rotation towards the positive Z-axis, while negative angles indicate a clockwise rotation towards the negative Z-axis, when viewed from above (i.e., looking down the Y-axis).

Cameras

Three cameras used for recording were GoPro 11. Cameras recording frame rate was 120 fps. And the shutter speed was 960 Hz. They were fixed on the participant with manual focus instead of automatic.

Software

Software used for analysing the videos was FreeMocap. (Matthis & Cherian, 2022) FreeMocap (Matthis & Cherian, 2022) is an open-source software that use mediapipe (Zhang et al., 2020) as a base model for 2D pose estimation and then use triangulation algorithms to do 3D pose estimation. To sync the videos for FreeMocap (Matthis & Cherian, 2022) use we used Adobe Premiere Pro audio sync feature.

Results

Hand movement during catching followed a consistent pattern: the hand opened to a maximum pregrasp aperture (MPA) and then closed around the ball upon contact. Importantly, the type of grip used varied systematically with ball size. Small balls elicited a power grip, in which the four fingers flexed deeply toward the palm while the thumb remained mostly stationary. This grip relied on wrapping the object securely within the palm without precise digit coordination, resembling a whole-hand enclosure. In contrast, large balls triggered a precision grip, where the hand opened wider and then closed in a coordinated manner, with the thumb and pinky pads forming the main opposing surfaces. This grip required fine control and oppositional contact, emphasizing the role of the thumb in stabilizing the object.

Kinematic data supported these differences: opposable distance (thumb to other fingers) and prehensile distance (fingers to palm) followed different trajectories for each grip type. Power grips showed minimal thumb motion and a strong inward sweep of digits 2–5, while precision grips featured a distinct late thumb movement toward the pinky for a secure closure. These patterns were confirmed in contact order heatmaps, which showed more consistent and sequential finger closure in power grips, versus variable and digit-specific coordination in precision grips. Together, these results demonstrate that grip type is not random but adaptively scaled to the object's size, with the sensorimotor system selecting between power and precision strategies to optimize control.

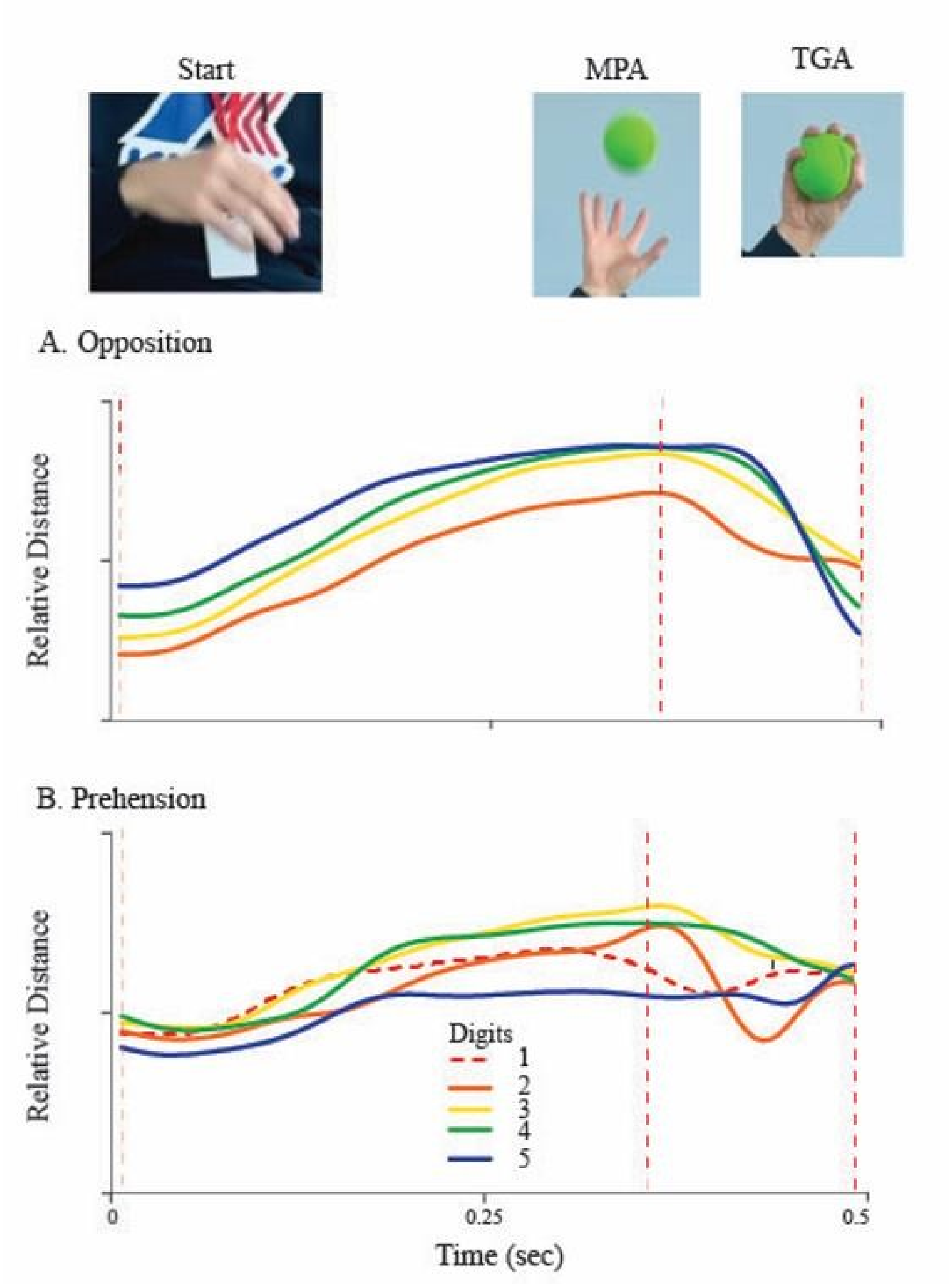


Figure 5. Movement sequence and kinematics precision-catch for the largest ball.

Photographic sequence.

1. **Start:** The participant begins with the catching hand resting on their lap.
2. **MPA (Maximum Pregrasp Aperture):** As the hand rises, all five digits extend and splay to their widest opening.
3. **TGA (Terminal Grasp Aperture):** After contact, the fingers flex inward to their final grasp, with the thumb and pinky pads forming the primary opposing surfaces.

Panel A. Opposable Distance

This plot charts each fingertip's planar separation from the thumb pad over time (Start → MPA → TGA):

- **Digits 2–5** fans outward from Start to their maximal distances at MPA.
- During closure, all four non-thumb digits move back toward the thumb, reducing the opposable distance.

Panel B. Prehensile Distance

This panel shows fingertip-to-palm distance on the same timeline:

- **Digits 2–5** begin at moderate distances, increase slightly as the hand opens beyond Start, and then dip markedly as they flex around the large ball for final purchase.

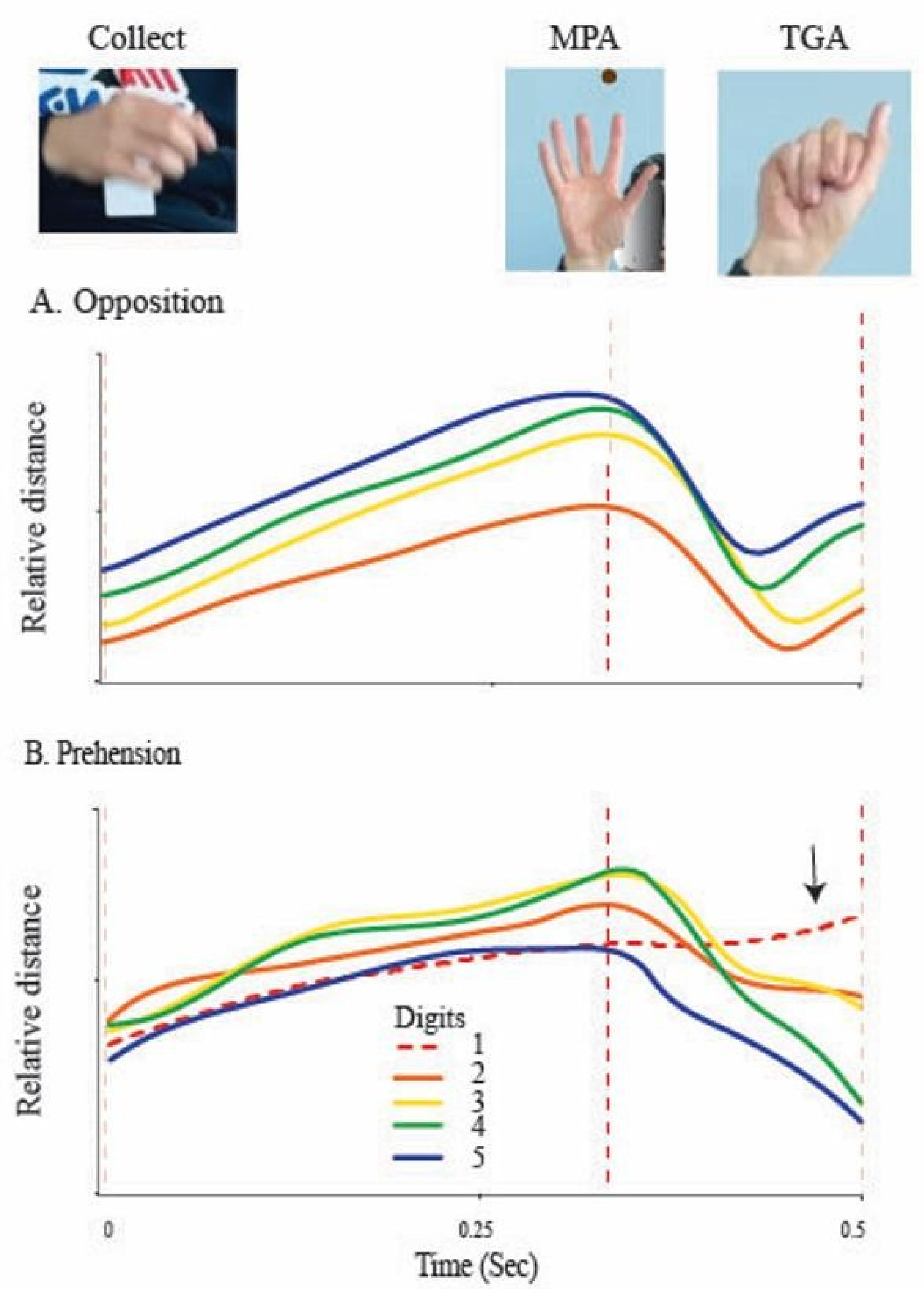


Figure 6. Movement sequence and kinematics of a power-catch for the smallest ball.

Photographic sequence.

1. **Collect:** The participant begins with the catching hand resting on their lap.
2. **MPA (Maximum Pregrasp Aperture):** As the participant raises the hand, the fingers extend and splay to form the largest opening before the ball arrives.
3. **TGA (Terminal Grasp Aperture):** After the ball contacts the palm, the fingers flex inward to their final grasp configuration, securing the ball without thumb involvement.

Panel A. Opposable Distance

This plot shows, over the time course of the catch (start → peak aperture → closure), how far each fingertip moves away from the thumb pad:

- **Digits 2–5** fan outward from the start position toward their maximal aperture at MPA, then go down toward TGA. However, as they wrap around the ball and pass the plane of the thumb, their measured distance from the thumb pad increases again just before TGA. This "dip-and-rise" reflects the fingers closing past the thumb and onto the ball's surface, momentarily extending their separation from the thumb before settling into the final grasp.

Panel B. Prehensile Distance

Here each fingertip's distance to the palm is plotted on the same time scale:

- **Digits 2–5** begin at moderate distances, increase slightly as the hand opens, then decrease rapidly after contact as the fingers flex to wrap around the ball.

- The **dashed line (Thumb)** stays flat throughout most of the trial, only moving minimally at the very end—highlighting the thumb's non-involvement in gripping the smallest ball during this power catch.

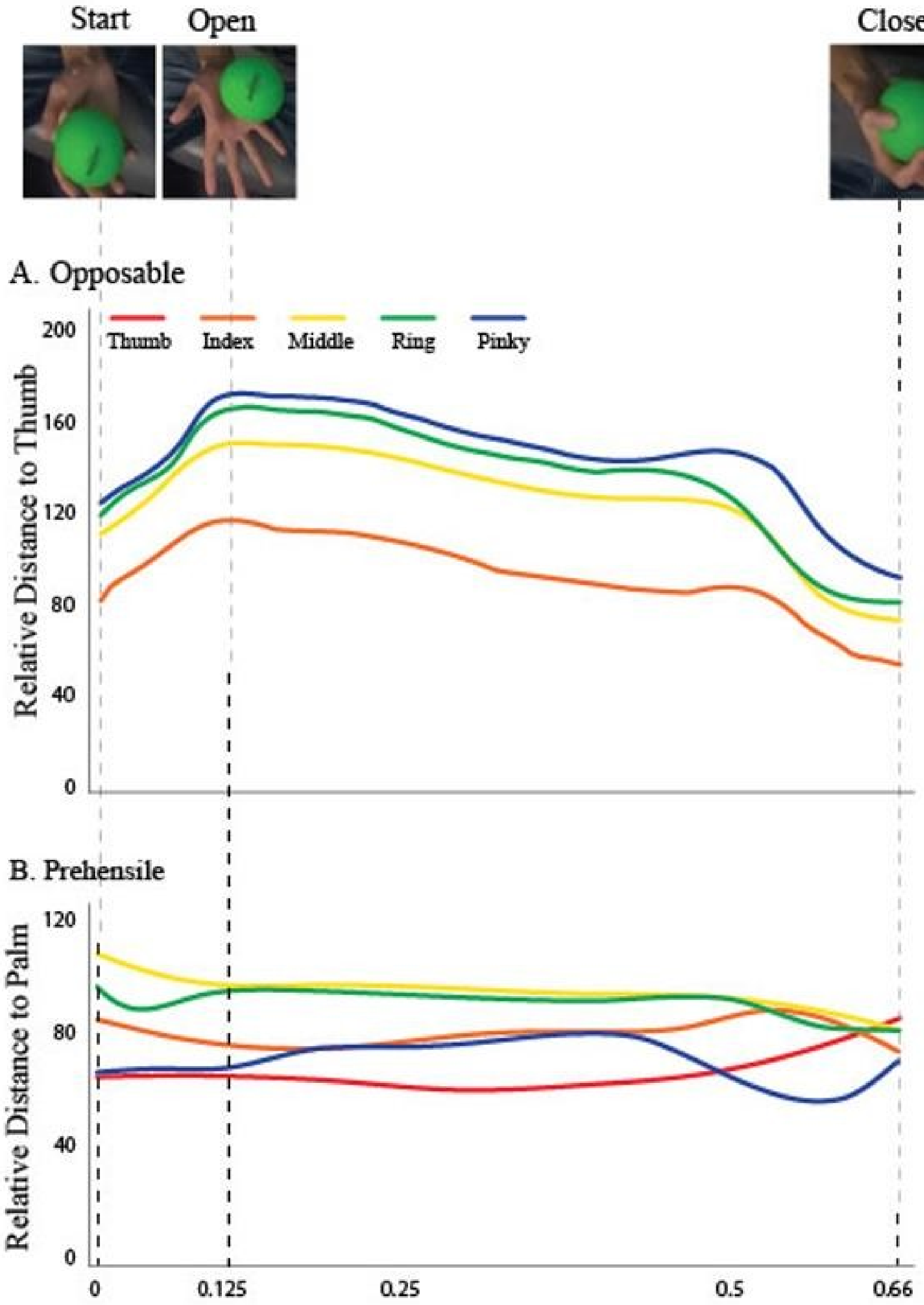


Figure 7. Hand configuration and kinematics during a self-catch of the largest ball using precision grip.

Photographic sequence.

- **Start:** The participant holds the large ball in the supinated palm at trial onset.
- **Open:** After release, the hand opens to its maximum pregrasp aperture, with all fingers widely splayed.
- **Closed:** Upon the ball's return and contact, the fingers flex inward to the terminal grasp aperture, securing the ball primarily between the thumb and pinky pads.

Panel A. Opposable Distance

This plot traces, over normalized catch time (Start → peak aperture → closure), the planar separation of each fingertip from the thumb pad. All non-thumb digits fan outward to reach their maximum distance from the thumb before reversing direction. The pinky achieves the largest outward excursion and is the last finger to converge back toward the thumb, highlighting its role in spanning the widest object.

Panel B. Prehensile Distance

Here each fingertip's movement toward the palm is shown on the same time scale. Following a slight dip as the hand opens, the four non-thumb fingers sweep back decisively toward the palm at the end of the catch. In contrast, the thumb remains relatively stationary during the initial opening but then moves markedly inward just before closure—illustrating its late yet critical engagement in opposing the pinky pad for a secure, precision-style grasp.

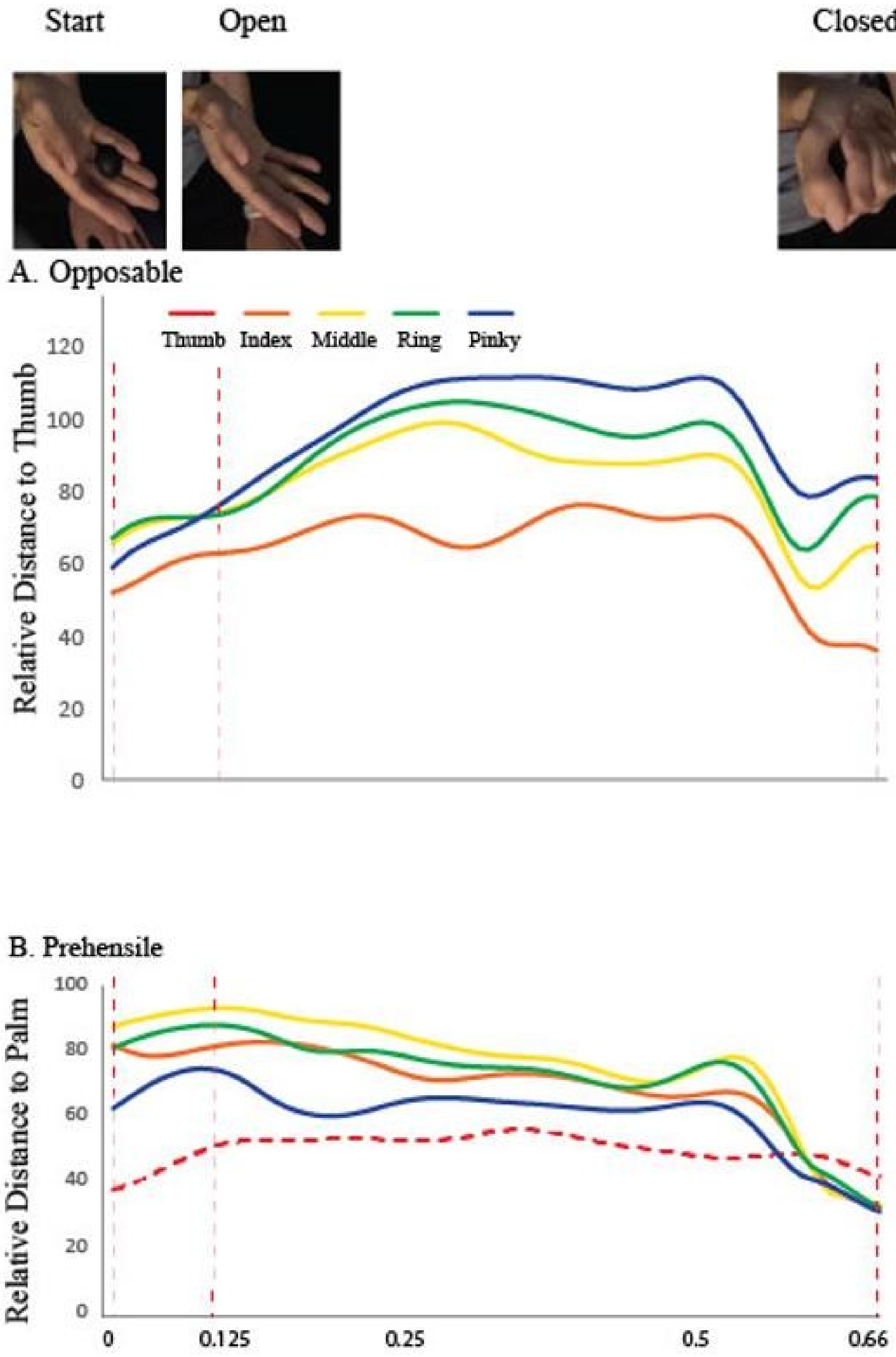


Figure 8. Hand configuration and kinematics during a self-catch of the smallest ball using power grip.

Photographic sequence

1. **Start:** The participant begins with the ball resting in the supinated palm.
2. **Open:** After release, the hand opens to its maximum pregrasp aperture, fingers widely splayed.
3. **Closed:** Upon ball return and contact, the fingers flex to the terminal grasp aperture, securing the ball in the palm.

Panel A. Opposable Distance

This plot shows, over a normalized catch time (0 = Start, first dashed line = Maximum Pregrasp Aperture, second dashed line = Terminal Grasp Aperture), the planar distance (mm) from each digit's pad back to the thumb pad ("opposable distance").

- **Index (orange), Middle (yellow), Ring (green), Pinky (blue)** each rise from the Start value to a peak at Maximum Pregrasp Aperture, then sharply decline toward closure.
- Notice the pinky achieves the largest peak distance and closes last, reflecting its role in enveloping the small ball.

Panel B. Prehensile Distance

This panel plots each digit's pad-to-palm distance (mm) on the same normalized time scale (same dashed vertical markers).

- **Solid lines (Index through Pinky)** begin at moderate distances, dip slightly as the hand opens further, then decrease steeply at the terminal phase as fingers flex onto the palm.
- **Dashed red line (Thumb)** remains relatively flat, indicating minimal thumb displacement in this power-grip scenario.
- Together, these traces illustrate that all four fingers flex substantially after contact while the thumb remains nearly stationary, characteristic of a whole-hand power grasp on a small object.

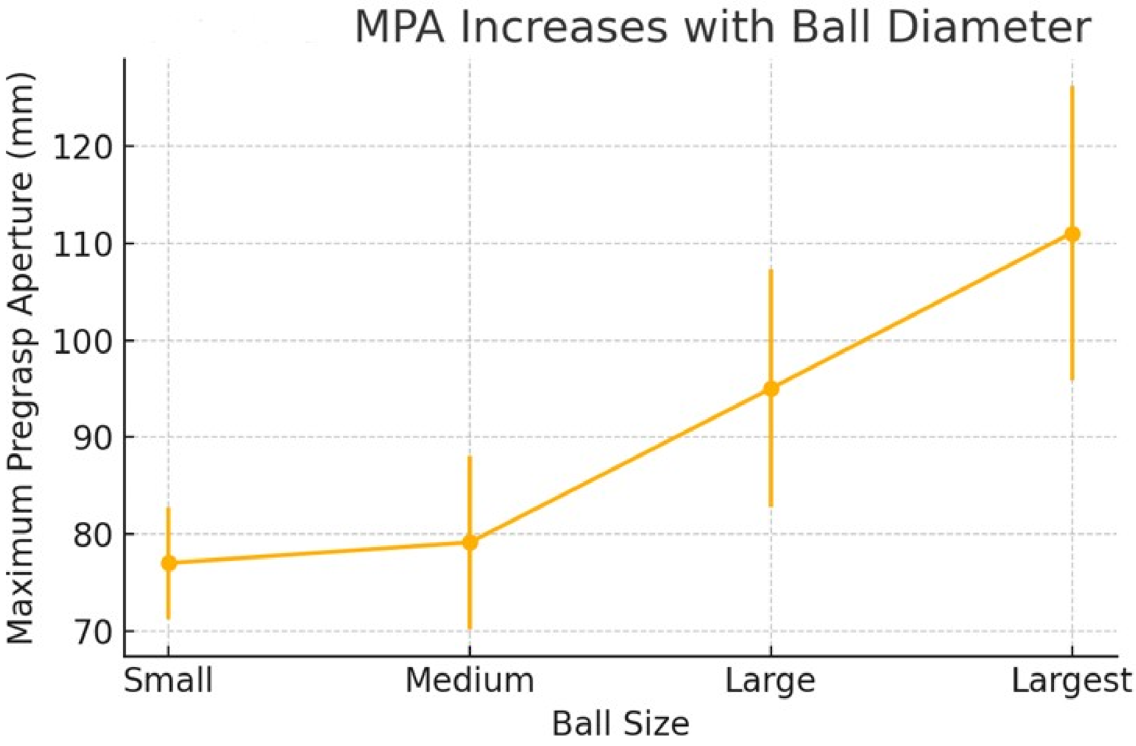


Figure 9. Maximum pregrasp aperture (MPA) increases with ball diameter. Error bars indicate 95% confidence intervals.

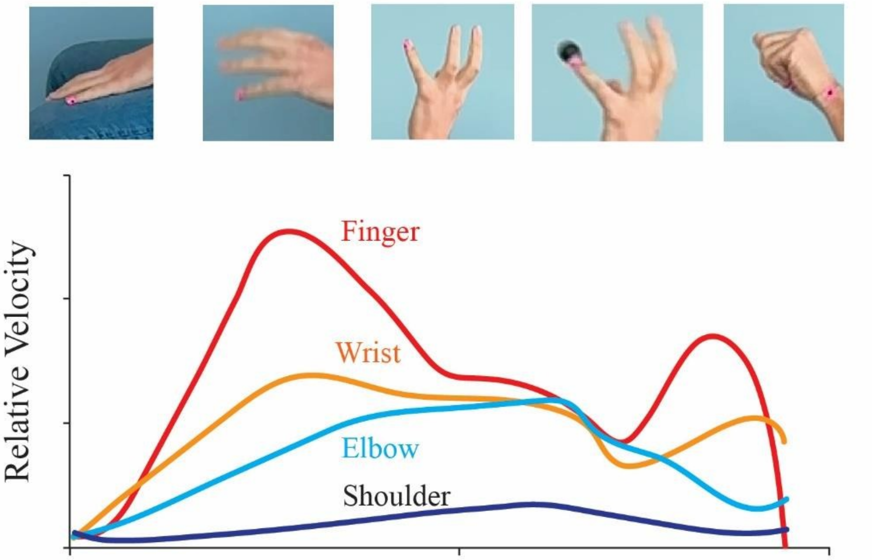
Maximum Pregrasp Aperture (MPA)

Figure 1 illustrates that MPA scaled linearly with ball diameter. Estimated marginal means (±SE) and 95 % CIs for each size were:

Ball Size	MPA (mm)	SE (mm)	95 % CI (mm)
Small	77.01	2.08	[71.24, 82.78]
Medium	79.13	3.22	[70.20, 88.07]
Large	95.02	4.42	[82.75, 107.30]
Largest	111.06	5.47	[95.86, 126.25]

A repeated-measures ANOVA confirmed a strong linear trend in MPA across sizes, $F(1, 4) = 81.11$, $p < .001$, $\eta_p^2 = .953$, and a significant omnibus effect of size, $F(3, 12) = 55.16$, $p < .001$, $\eta_p^2 = .932$. Bonferroni-adjusted pairwise contrasts showed that both Large vs. Small ($\Delta = 18.01$ mm, SE = 3.39 mm, $p = .036$, 95 % CI [1.56, 34.46]) and Largest vs. Small ($\Delta = 34.04$ mm, SE = 3.97 mm, $p = .006$, 95 % CI [14.80, 53.29]) were significant, whereas the Small vs. Medium difference was not ($p = 1.000$).

A. Chase catch



B. Stop catch

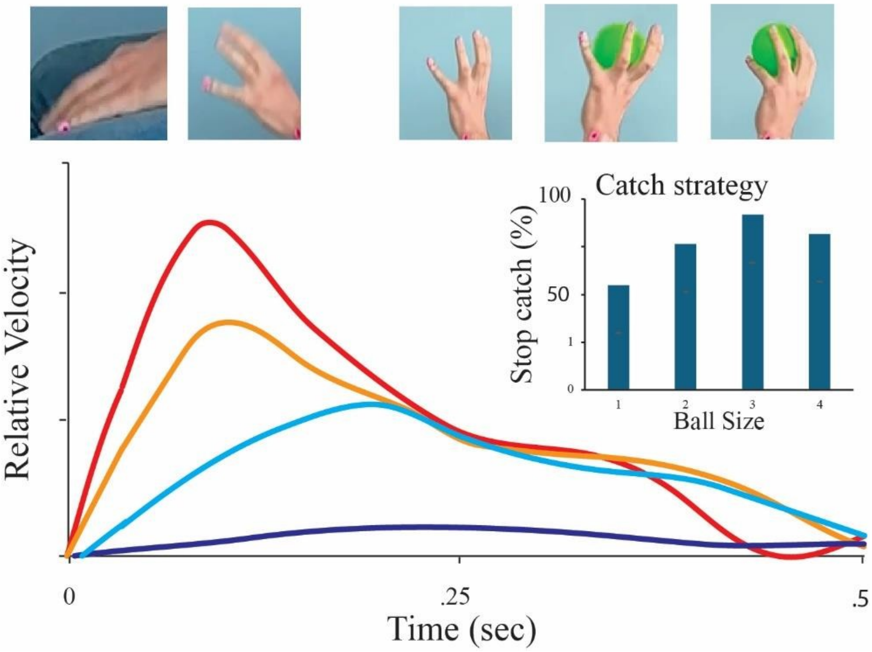


Figure 10. This figure shows the velocity of each hand component when catching for the smallest ball and the large ball.

Velocity profiles, measured at the tip of the pinky (finger 5), wrist, elbow, and shoulder, indicate that the catch is initiated by movement of the lower arm followed by movement of the upper arm when catching both the smallest ball (Figure 10A) and a large ball (Figure 10B). Figure 10 also provides an example of a chase catch used to catch the smallest ball, in which the hand accelerates forward as the digits are closed. A forward movement is associated with forward movement at the shoulder. Figure 10B gives an example of a stop catch, associated with catching the larger ball, in which the hand stops the ball and the digits concurrently close to trap it.

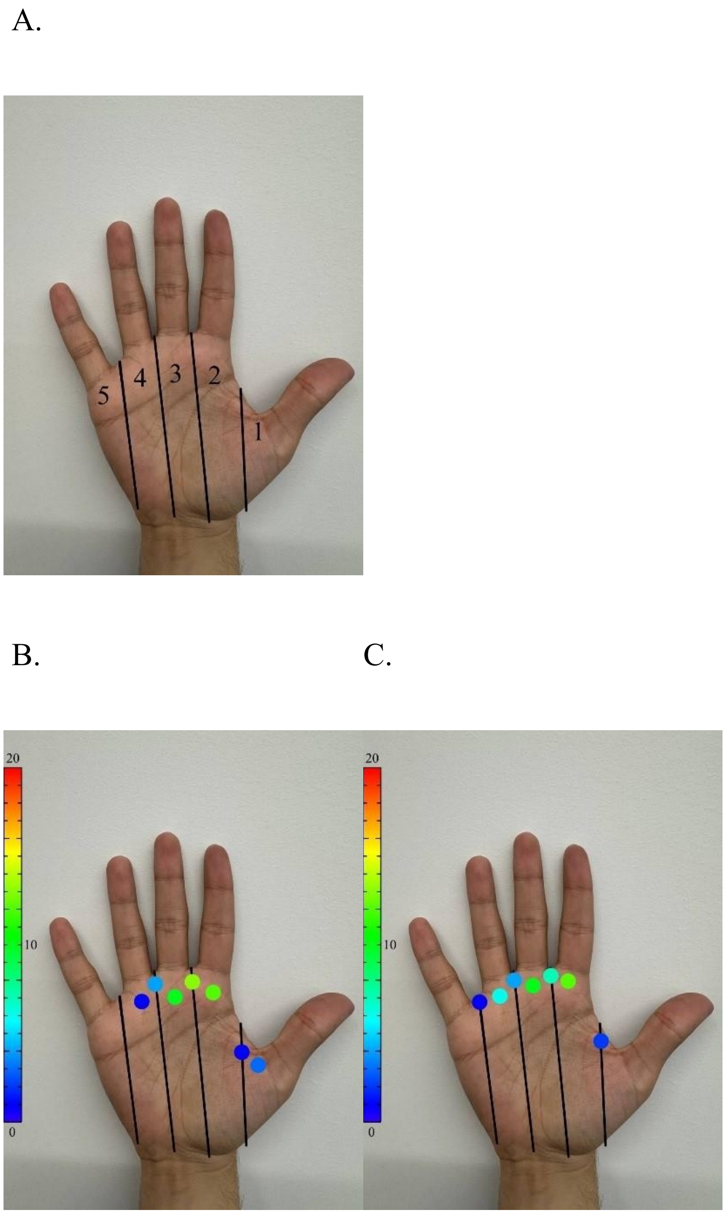


Figure 11. Illustrates a heatmap-based spatial analysis of where the ball contacted different hand regions during catching tasks with varying ball sizes.

Panel A shows the hand segmentation methodology, where the hand is systematically divided into distinct regions using a grid system. The numbered regions (1-5) create standardized zones for quantifying ball contact locations during catching trials.

Panels B and C present heat map visualizations comparing contact patterns between large ball (Panel B) and small ball (Panel C). The color-coded scale indicates contact frequency or intensity, with warmer colors (red/orange) representing higher frequency contact zones and cooler colors (blue/green) indicating lower frequency areas.

The comparison reveals counterintuitive contact pattern differences based on ball size. For large balls (Panel B), contact points are more concentrated in the index finger region of the palm, showing a focused contact pattern despite the ball's larger size. In contrast, small balls (Panel C) demonstrate more diverse and distributed contact patterns across multiple hand regions, suggesting greater variability in contact locations.

This finding indicates that larger balls may be caught using more consistent, predictable contact strategies focused on the index finger-palm region, while smaller balls require more varied hand positioning and contact approaches. The blue dots overlaid on both panels mark specific contact locations, highlighting this size-dependent difference in contact consistency.

This spatial analysis provides insight into how catching strategies adapt to ball size, with larger objects potentially allowing for more stereotypical hand positioning while smaller objects require more flexible and variable contact strategies.

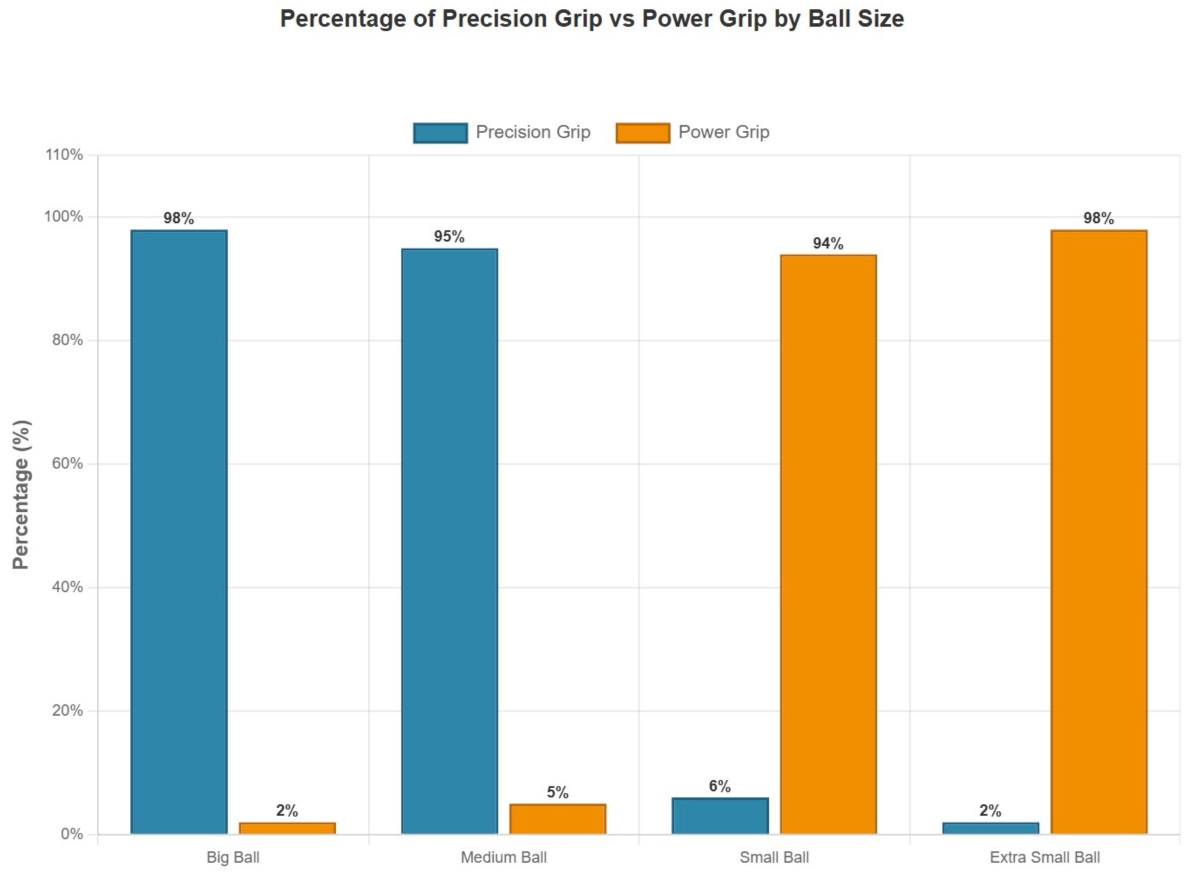
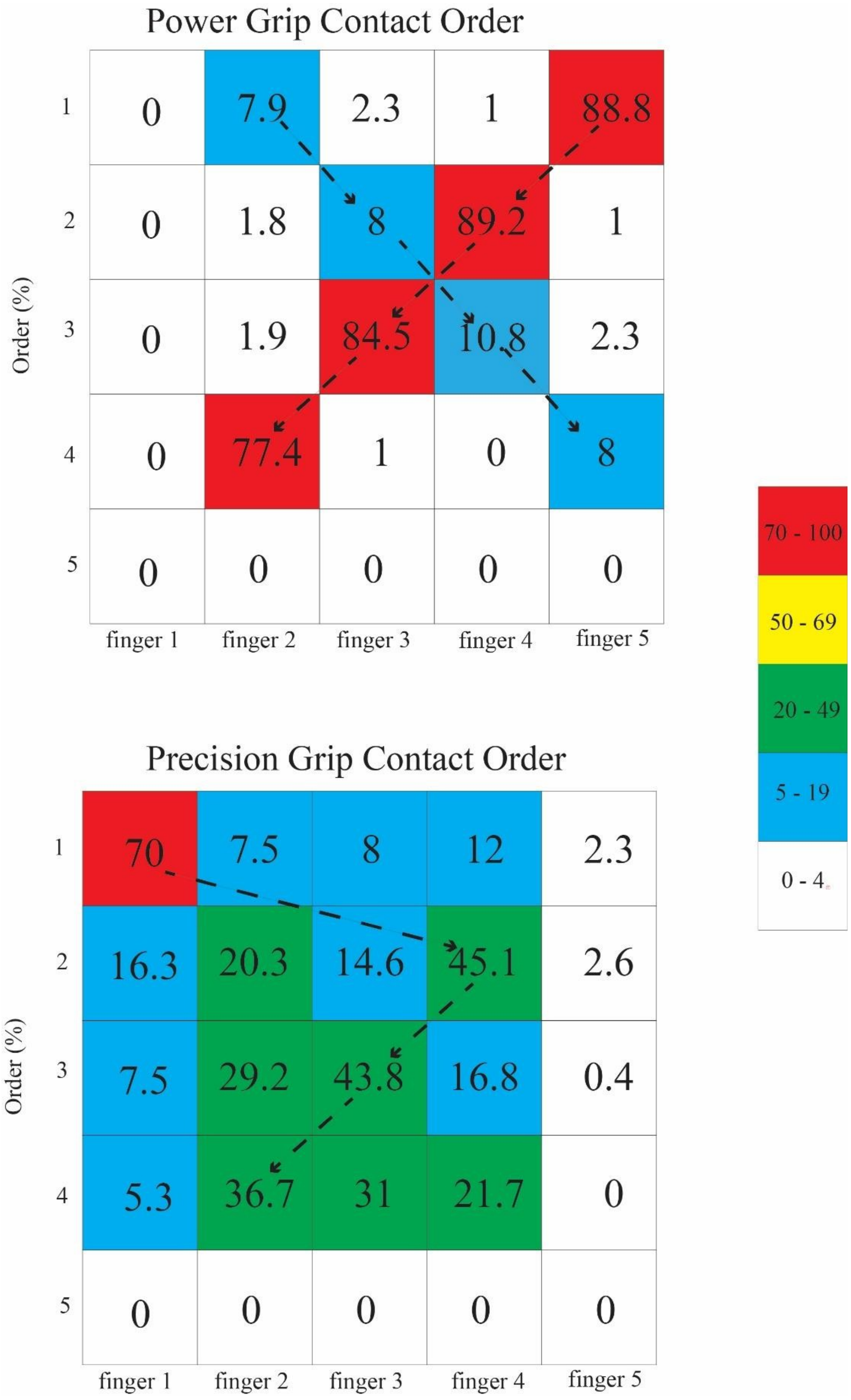


Figure 12. Percentage of precision grip and power grip usage across different ball sizes.

The bar chart shows precision grip (blue bars) and power grip (orange bars) percentages for four ball sizes. Big balls showed 98% precision grip and 2% power grip. Medium balls showed 95% precision grip and 5% power grip. Small balls showed 6% precision grip and 94% power grip. Extra small balls showed 2% precision grip and 98% power grip.



Power Grip Contact Order

Order (%)	finger 1	finger 2	finger 3	finger 4	finger 5
1	0	7.9	2.3	1	88.8
2	0	1.8	8	89.2	1
3	0	1.9	84.5	10.8	2.3
4	0	77.4	1	0	8
5	0	0	0	0	0

Precision Grip Contact Order

Order (%)	finger 1	finger 2	finger 3	finger 4	finger 5
1	70	7.5	8	12	2.3
2	16.3	20.3	14.6	45.1	2.6
3	7.5	29.2	43.8	16.8	0.4
4	5.3	36.7	31	21.7	0
5	0	0	0	0	0

Figure 13. finger closing order heatmaps for power grip and precision grip.

The upper heatmap shows power grip contact order with two main trends: the predominant pattern follows a 5-4-3-2 closing sequence, while a less frequent pattern shows a 2-3-4-5 closing order. The lower heatmap shows precision grip in contact order with more diverse patterns across fingers, but the most common sequence follows a 1-4-3-2 closing order. Both grip types show no activity in the fifth contact order. The color scale ranges from white (lowest values) through blue and green to red (highest values).

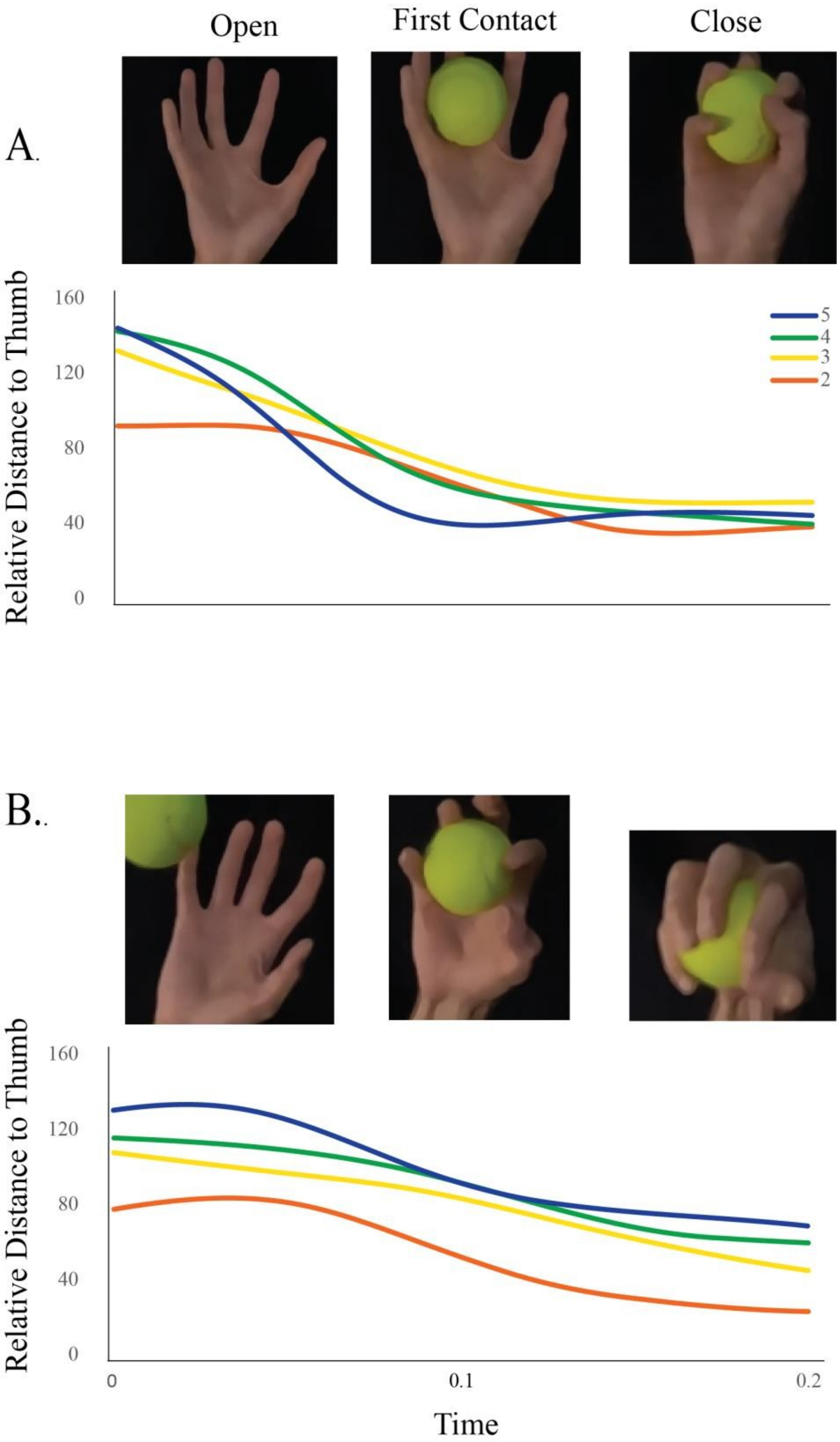


Figure 14. Relative distance to thumb while grasping for different ball landing positions.

Panel A shows a ball landing close to the pinky side with sequential images of open hand, first contact, and closed grip. The graph displays relative distance to thumb over time for fingers 2-5, with all fingers starting at high distances and decreasing as the hand closes. Panel B shows a ball landing close to the index finger side with corresponding sequential images. The graph shows similar distance patterns with fingers 2-5 trajectories converging toward lower distances over the 0.2 second time period. Different colored lines represent individual fingers (blue, green, orange, yellow), tracking their proximity to the thumb during the grasping motion.

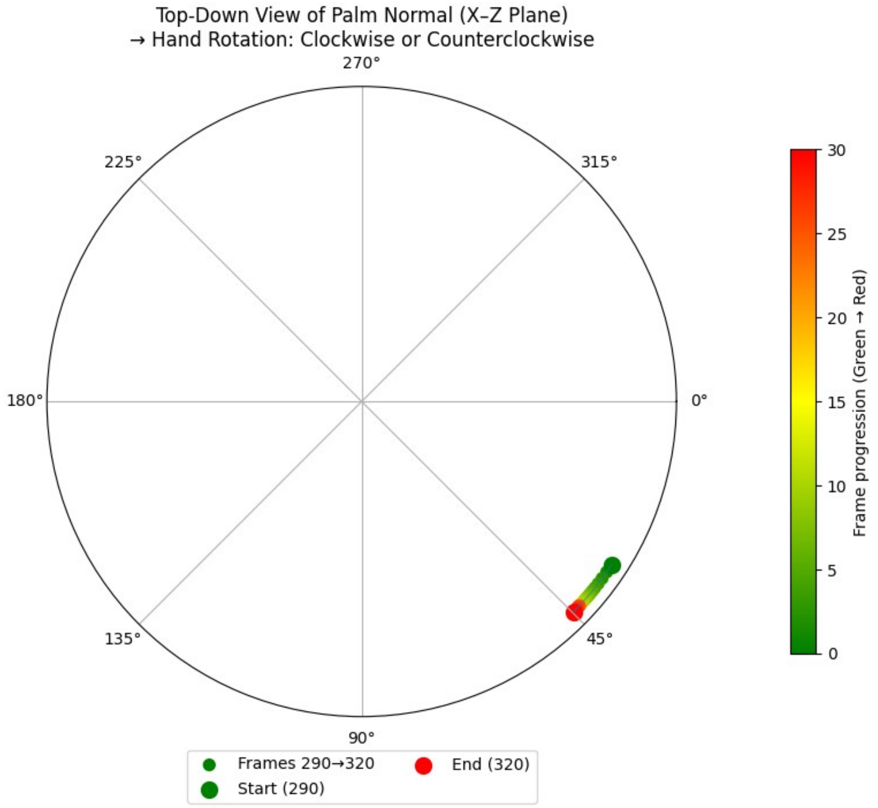


Figure 15. Top-down view of palm normal showing hand rotation during grasping (for figure 14A).

The circular plot displays hand orientation in the X-Z plane with angular measurements from 0° to 360°. The green circle indicates the start position at 30°, and the red circle shows the end position at 45°. The movement from start to end demonstrates a clockwise rotation representing supination of the hand. The color scale on the right ranges from 0 to 30, indicating frame progression over time. Radial grid lines mark every 45° around the circle with cardinal directions labeled.

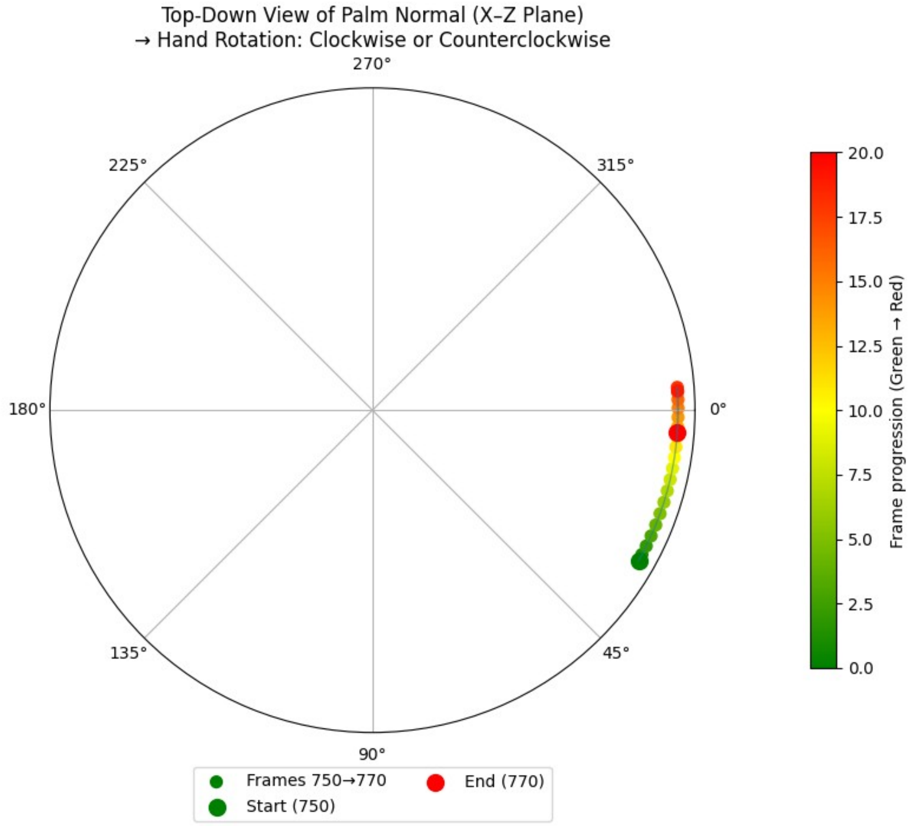


Figure 16. Top-down view of palm normal showing hand rotation during grasping. (for figure 14B)

The circular plot displays hand orientation in the X-Z plane with angular measurements from 0° to 360°. The green circle indicates the start position at 30°, and the red circle shows the end position at 5°. The trajectory shows a curved path with color-coded points representing frame progression from green (early frames) through yellow to red (later frames). The movement demonstrates counterclockwise rotation. The color scale on the right ranges from 0 to 20.0, indicating frame progression over time. Radial grid lines mark every 45° around the circle with cardinal directions labeled.

Discussion

This thesis investigated how grip formation during catching is influenced by object size, impact location, and movement dynamics, and how these factors relate to competing theories of prehension—specifically Jeannerod's Dual Visuomotor Channel (DVC) theory and Smeets and Brenner's digit-specific control model. Using 3D pose estimation, the study analyzed hand kinematics across catching tasks with balls of varying sizes.

Three key findings emerged: (1) Grip-type reversal occurred with object size—small balls were caught using whole-hand power grips, while large balls required precision grips involving thumb–pinky coordination. (2) Maximum Pregrasp Aperture (MPA) increased linearly with ball size, supporting DVC's concept of anticipatory shaping guided by intrinsic object features. (3) In 50% of small-ball trials, chase-catch overshoots were observed, reflecting a delay between contact and full closure, consistent with open-loop momentum followed by feedback correction.

While the results strongly support the DVC framework, especially for precision grasps, they only partially align with Smeets and Brenner's model. In particular, the thumb's passive role during power grips contradicts the expectation of fully independent digit control. However, variation in finger closure sequences and impact-driven modulation of closure timing suggest that grasping strategies are context-sensitive and flexible.

These findings refine our understanding of naturalistic visuomotor control and carry practical implications for robotic grasping, neurorehabilitation, and adaptive human–machine interfaces.**1.**

1. Summary of Aims and Key Findings

The research uncovered three main insights into how we catch:

1. **Grip Style Adapts to Ball Size:** People changed their grip depending on the size of the ball. For small balls, they typically used a **"power grip,"** where all the fingers curl to hold the ball tightly against the palm. For larger balls, they switched to a **"precision grip,"** using the thumb and pinky finger to grasp the ball from opposite sides.

2. **The Hand Knows the Ball's Size in Advance:** Before the ball even arrived, participants opened their hands wider for larger balls. This anticipatory action, called **Maximum Pregrasp Aperture (MPA)**, scaled directly with the ball's size. This shows that the brain plans the hand's shape based on the object's visual properties.

3. **The "Chase-Catch" Effect:** In about half of the trials with small balls, the hand continued to move forward for a moment *after* making contact, before closing its grip. This "overshoot" or **"chase-catch"** suggests the hand is acting on a pre-planned path, and it takes a fraction of a second for the brain to process the touch and make the final adjustment to stop and secure the ball.

2. Theoretical Interpretation

These results help us understand a few key theories about how our brains control movement:

- **Napier's Grip Classification**: A scientist named J.R. Napier was one of the first to categorize hand grips into "power" and "precision" types. This study's findings directly support Napier's distinction, showing that we naturally switch between these two fundamental grips based on the object's size.

- **The Dual Visuomotor Channel (DVC) Theory**: This theory suggests that our brain uses two separate pathways for grasping an object. One pathway, the "reach" channel, moves the hand to the object's location. The other, the "grasp" channel, shapes the hand based on the object's size and shape. The fact that the hand's opening (MPA) was pre-set according to the ball's size strongly supports the existence of this "grasp" channel, as the hand was shaped in anticipation of the catch.
- **Smeets and Brenner's Model**: This alternative theory proposes that grasping is simply the independent movement of the thumb and fingers toward specific points on an object. The study's results only partially support this. While precision grips showed fingers moving to specific locations, the power grips for smaller balls saw the thumb remain mostly passive, which contradicts the idea that all digits always act independently.

3. Practical and Theoretical Implications

Rehabilitation

Practicing catches with balls of different sizes can help retrain both large hand movements (power grasps) and smaller, more precise ones (precision grasps). In people recovering from stroke or dealing with motor problems, this kind of training can improve how well they plan and adjust hand movements. Two useful markers are MPA scaling (how wide the hand opens based on ball size) and chase-catch frequency (how often the hand needs to correct its path). These can show whether someone is using more predictive or reactive control and help guide rehab programs to restore natural movement (Bernhardt et al., 2017).

Robotic Grasping

Robots often have trouble picking up moving or unknown objects. This research suggests that robots should pre-set their hand opening based on how big the object looks. Then, they should use a short, quick move (open-loop phase) followed by a braking phase to secure the object smoothly. This mirrors how humans catch—starting fast and adjusting near the end. These ideas could help make robot hands more flexible and natural in real-world tasks (Bicchi & Kumar, 2000).

Neuro prosthetics

Catching tasks show how the brain plans and controls grip in real time. These patterns could help train brain-controlled prosthetic hands to work more like real hands. If prosthetics can predict how wide to open and when to close based on brain signals, they would become more useful for everyday activities (Mussa-Ivaldi & Solla, 2003).

Human–Machine Interaction

Wearable tech like VR gloves or robotic arms needs to respond quickly and accurately to human movements. Findings from this study—like when the thumb joins the grasp or how fast the hand adjusts—can help build smarter and safer systems. Adding features that copy how humans move, such as momentum-aware corrections, can make machines feel more natural to use (Ajoudani et al., 2018).

4. Limitations

- **Participant Demographics.** Young, right-handed undergraduates; broader populations remain to be tested.

- **Tracking Precision.** camera pose estimation introduces spatial error (~10 mm) affecting overshoot measurement.
- **Overshoot Quantification.** We recorded chase-catch prevalence but lacked precise measures of overshoot distance and timing.

5. Future Directions

1. Study people with brain injuries or movement disorders, such as stroke or Parkinson’s disease, to see how catching and grip control are affected. This could help design better rehabilitation programs that target specific movement problems.
2. Include a wider range of participants, such as older adults, children, and left-handed individuals. This would show whether the results apply to different ages and types of motor control.
3. Use more accurate motion capture systems, like Vicon, to better measure how far and how fast the hand moves during catching, especially in the chase-catch phase.
4. Change the speed and direction of the ball in future tests to better understand how people adjust their movements when the object is harder to predict.
5. Look more closely at where the ball hits the hand, and how that changes the way fingers close. Using hand sensors could help link contact location to grip behavior.
6. Analyze finger-closing patterns with better tools, like machine learning or clustering, and include quality scores (like silhouette scores) to show how reliable the patterns are.
7. Apply these findings to robotics and prosthetics, to help create devices that grasp objects more like a human hand—by planning ahead and adjusting based on touch.

6. Conclusion

The purpose of this thesis was to explore how grip formation during catching reflects different theories of prehension—especially Jeannerod's Dual Visuomotor Channel (DVC) theory and Smeets and Brenner's model of digit-specific control. Ball size was used to represent intrinsic object features, and 3D motion tracking was used to examine how the hand and fingers moved across different catching tasks.

The results strongly support key ideas from the DVC theory. Maximum Pregrasp Aperture (MPA) increased with ball size, showing that the hand opens in advance based on the expected size of the object—consistent with feedforward planning. Larger balls were usually caught using precision-style grips, where the thumb and pinky worked together to hold the object—matching the DVC idea of separate reach and grasp systems.

Smaller balls, on the other hand, were caught using power grips, where the fingers flexed toward the palm and the thumb remained mostly still. This goes against Smeets and Brenner's idea that both the fingers and thumb always move independently toward specific contact points. However, the variation in finger closure patterns, and the way impact location influenced which fingers closed first, suggests that finger movements are flexible and can adapt to the task—even if not exactly in the way their model describes.

The chase-catch overshoots seen in many small-ball trials show that the hand sometimes continues moving forward after contact before fully closing. This reflects a short phase of open-loop control, where the movement is based on prediction, followed by feedback corrections—a process supported by models that separate planning from feedback.

Overall, the results show that the DVC theory better explains how the hand prepares for and performs precision grasps, especially for larger objects. Smeets and Brenner’s model is not fully supported, mainly because the thumb did not show the independent role their theory predicts. Still, the flexibility in how fingers close and the effect of where the ball hits the hand show that grasp control is adaptive and shaped by context.

These findings help us better understand how the brain controls hand movements during catching and may be useful in fields like robotics, rehabilitation, and human–machine interaction, where flexible and adaptive grasping is essential.

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