Opinion-Perspective Article

A Constrained Multi-DOF Metacarpophalangeal Joint for Upper-Limb Prostheses

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ABSTRACT

Upper limb amputees often face challenges and struggle performing everyday tasks that require dexterity, grip adaptability, and precise finger control. Although modern prosthetics have improved through advances in myoelectric control systems, improved materials, and even customizable manufacturing, many devices remain restricted by simplified mechanical joint designs. In particular, most prosthetic fingers rely on single-axis hinge joints that only allow flexion and extension, eliminating lateral motion and reducing the natural degrees of freedom in human metacarpophalangeal (MCP) joints. This mechanical constraint limits the effectiveness of advanced control systems and prevents hands from fully replicating natural finger movement. To address this limitation, our research proposes a prosthetic finger design that incorporates a constrained ball-and-socket joint at the MCP position to increase degrees of freedom (DOFs) while maintaining stability and control. The joint is engineered with internal mechanical stops that replicate ligament-like constraints, restricting motion to biologically realistic ranges of flexion, extension, and controlled adduction/abduction. The design is intended to integrate tendon-driven actuation, myoelectric EMG-based interfaces, and vibrotactile feedback to support coordinated movement while minimizing cognitive load for the user. Additionally, manufacturing techniques such as 3D printing are proposed to enable lightweight, customizable, and cost-effective production. The functionality of the proposed prosthetic can be evaluated using standardized assessments, including the Prosthetic Hand Assessment Measure (PHAM) and the Box and Block Test (BBT), to determine whether increased mechanical degrees of freedom translate into measurable improvement in dexterity and task performance. As this is a conceptual design that has not yet been prototyped, the anticipated benefits described above are presented as hypotheses to be evaluated through future fabrication and testing. Overall, this design aims to narrow the gap between anatomical realism and practical prosthetic usability, with the potential to improve functional outcomes and accessibility for upper-limb amputees.

Keywords: Biomedical Engineering; Prosthetic Hand Design; Metacarpophalangeal Joint; Ball-and-Socket Joint; Myoelectric Control

INTRODUCTION

Upper-limb amputees, consisting of about 35% of total amputees nationwide, struggle to adjust to completing common daily tasks and maintain their own quality of life (1). However, commercial prosthetic hands usually fail to achieve their full functional potential due to limitations, particularly in joint design, cost, and weight. The open issues referring to upper limb prostheses include the lack

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of functionality and discomfort due to high weight, and most devices are unaffordable (2). Many devices rely on simplified hinge-like joints that completely restrict natural finger motion and reduce independent motor function, limiting their dexterity and adaptability. A large majority of hand prostheses incorporate simple hinge and gimbal-type joints, and in most prosthetic hands, all fingers, excluding the thumb, have only planar motion — flexion and extension (3). As a result, even advanced control systems cannot fully replicate human hand movement because the mechanical joints themselves constrain and restrict the natural biological function of the metacarpophalangeal joint. In recent years, advances in technology have significantly impacted the feasibility and effectiveness of prostheses. For instance, myoelectric control systems rely on muscle signals to drive movement in prostheses. The myoelectric prosthetic hand is based on electromyographic (EMG) signals generated in skeletal muscles, which reflect the user's movement intentions (4). Despite these advancements, the systems are closely tied to joint design. Because many prostheses use uniaxial joints with limited degrees of freedom, the mechanical characteristics of current prostheses restrict fine motor control and prevent myoelectric systems from fully replicating the natural coordinated motion of normal human finger joints. Myoelectric control presents numerous limitations, including difficulty when managing simultaneous movements and few degrees of freedom (5).

Although prosthetics have advancements in control systems such as myoelectric interfaces, they remain limited by simplified joint designs that restrict natural finger motion and fine motor control (1). Building on this, this paper proposes a different mechanical design: a constrained ball-and-socket joint at the finger base intended to provide increased degrees of freedom. This design is intended to more closely replicate normal human hand anatomy while maintaining controlled, stable movement. By intentionally limiting the joint range to prevent hypermobility, this design aims to balance enhanced dexterity with reliable control. Furthermore, the design proposes to use 3D printing for parts of manufacturing to keep it lightweight, customizable, and lower cost, increasing accessibility for amputees.

BACKGROUND

Current Technology

Historically, technological constraints have limited the complexity of prosthetic joint mechanisms. From A.A. Marks with his technological innovations during World War 1 to Reinhold Reither creating the first myoelectric prostheses in 1948, prosthetic devices have continuously improved into the models seen today (6). Modern prosthetics are characterized by improved functionality via improved materials, electronics, and 3D printing.

For instance, the integration of 3D printing in the production of prosthetics has been transformative. Systematic reviews show that 3D printing and scanning are not just theoretical tools in prosthetic research but are actively shaping how hand and finger prostheses are being developed (7). Researchers have begun to focus more on finger-specific designs and advanced control systems, using scanners to model detailed limb shapes so that they are able to quickly produce prototypes that can be customized per a user's individual anatomy. However, despite these clear advantages, the field has not yet solved many practical issues. One major factor is that 3D printed hands often underperform due to durability concerns; inexpensive plastics such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) may deform, crack, or wear out over time through everyday use (7). This limits long-term use outside of controlled testing environments. While 3D printing shows promise for manufacturing prostheses, more comprehensive studies and advancements are needed to overcome existing challenges and enhance the functionality of these assistive products (8).

The Challenge at Hand

While modern prosthetic devices are significant improvements compared to prosthetics of the past, there still remain many areas for improvement. For instance, many prosthetics have a limited range of motion and can benefit from improved degrees of freedom to better mimic biological function. Also, prostheses have improved fine motor control over the years through advancements such as myoelectric systems, but still struggle with very fine tasks that require large amounts of precision. Lastly, many prosthetics include hinge joints, which restrict the ability to adapt to complex cases in which different positions are needed (9).

Human finger joints, particularly the metacarpophalangeal (MCP) joints, naturally allow multi-planar motion including flexion/extension and abduction/adduction, enabling fine motor control and hand dexterity (10). In contrast, many prosthetic hands rely on simplified uniaxial hinge joints that permit movement in only one plane, eliminating lateral motion and reducing functional degrees of freedom (11). While this design improves stability and ease of control, it prevents prosthetic fingers from replicating natural joint biomechanics and limits adaptability during complex or precise tasks, making joint design a key mechanical limitation in current prosthetic hand technology.

Building on the 3D-printing capabilities described above, recent advances in 3D printing manufacturing have further expanded the scope of producing functional, low-cost prosthetic devices, particularly for upper-limb applications. Multiple studies show that 3D printing enables quick prototyping, customization to individual anatomy, and substantial reductions in material and manufacturing costs compared to traditional machining methods (11). Research on 3D-printed hand prostheses shows that lightweight polymer materials can achieve sufficient strength and durability for daily tasks through utilizing complex internal structures that are difficult to fabricate using traditional techniques (12). Additionally, modular and replaceable components made through 3D printing have been shown to improve accessibility and ease of repair, which is especially important for pediatric and underserved communities (11). These findings suggest that additive manufacturing provides a practical pathway for producing mechanically sophisticated prosthetic hands while maintaining affordability and scalability (13).

Research in prosthetic hands has sought to increase the number of degrees of freedom (DOF) to better mimic human biology. Traditional prosthetic hands typically rely on a single-axis hinge joint, which is mechanically simple, lightweight, and straightforward to control, but which significantly limits dexterity and restricts complex grasping patterns even when paired with advanced control systems (9). Gimbal-type joints extend this approach with a second axis of motion, offering modestly improved dexterity at the cost of additional linkages, weight, and control complexity. Ball-and-socket joints represent a further step: in principle, they can provide three rotational degrees of freedom within a single compact mechanism that more closely mirrors the condyloid motion of the biological MCP joint. However, this added motion introduces its own engineering challenges, including more complex constraint geometry, a greater risk of unintended or unstable motion without internal mechanical stops, and a higher-dimensional control problem for the user. In recent years, researchers have designed spherical ball-and-socket joints for the prosthetic thumb, achieving a minimum of three DOF characteristic of human thumb kinematics. These findings indicate a clear need for prosthetic joint designs that increase anatomical realism and motion capability while maintaining controlled, stable movement, but they also illustrate that ball-and-socket designs have so far been applied primarily to the thumb rather than to the finger MCP joints. The design proposed in this paper differs in that it applies a constrained ball-and-socket architecture to the finger MCP joint specifically, with internal mechanical stops calibrated to MCP-specific physiological ranges rather than thumb kinematics. Overall, existing prosthetic research demonstrates that while advances in control systems and manufacturing have improved usability, the joint design itself remains a limiting factor: the most prominent constraint being restricted DOF, which prevents prosthetic hands from achieving natural, stable, and functional movement (14).

MECHANICS OF THE PROPOSED JOINT

Joint Biomechanics

The metacarpophalangeal (MCP) joint of the hand is biomechanically complex. Functioning as a condyloid joint, the MCP joint has two primary active degrees of freedom: flexion/extension and adduction/abduction. In addition, the MCP joint has passive axial rotation, which contributes to gripping and fine motor control (15). In a normal MCP joint, flexion typically approaches approximately 90°, extension ranges from approximately 10–30°, adduction/abduction averages ±20–30° aligned with the frontal plane for most fingers, and passive axial rotation may range from 30–40° (16). This enables the coordinated motion necessary for both precision and powerful grasps. As discussed above, most conventional prosthetic hands simplify these complex mechanics into single-axis hinge joints that allow only flexion and extension, eliminating lateral movement and rotational adaptability. As a response to these biomechanical limitations, our proposed design specifies a constrained ball-and-socket MCP unit intended to approximate physiological motion while preserving mechanical stability. The design targets about 80–90° of flexion, 20° of extension, and 20° of controlled adduction/abduction, closely mirroring functional biological ranges. Additionally, limited passive axial rotation may be included if structural safety and control integrity can be maintained. External geometric constraints within the socket are intended to restrict excessive motion and reduce the risk of instability, with the goal of allowing increased DOFs to enhance grasp adaptability without compromising controllability. By grounding the joint design in established MCP biomechanics while applying deliberate mechanical limits, the proposed design aims to narrow the gap between anatomical realism and practical prosthetic reliability.

Mechanical Constraints and Stops

To help ensure that ball-and-socket MCP joints remain biomechanically safe and functionally stable, the proposed design incorporates mechanical travel limits that replicate the natural constraints imposed by ligaments in the human hand. In the biological MCP joint, ligaments restrict excessive motion, preventing hyperextension, hyperflexion, and extreme lateral deviation while still permitting functional ranges necessary for grasping. To mirror these protective mechanisms, the prosthetic joint integrates internal mechanical stops calibrated to physiological limits: flexion is restricted near 90°, extension near 20°, and adduction/abduction near ±20°. These internal constraints are embedded directly into the socket geometry and are intended to keep motion within safe and anatomically appropriate boundaries even under load. By mechanically enforcing these limits, the design is intended to reduce the likelihood of unstable or unnatural movements that could compromise control, structural integrity, or user safety. In effect, the constrained ball-and-socket architecture seeks to replicate ligament-based stabilization through engineered geometry, with the goal of allowing increased degrees of freedom while limiting the risk to reliability or precision.

Because the proposed design is intended for use in a human-assistive device, potential failure modes must also be considered. First, ball dislocation from the socket is possible under extreme lateral loads; the internal mechanical stops and socket geometry are intended to mitigate this, but the adequacy of these constraints will need to be confirmed through mechanical stress testing. Second, repeated cyclic loading may cause wear at the mechanical stop surfaces over time, particularly if low-cost polymer materials such as PLA or ABS are used; future prototyping should evaluate material selection and apply appropriate safety factors to account for long-term wear. Third, tendon cables routed through the fingers are subject to fatigue failure under repeated loading, and actuator overload is a risk if grip forces exceed design targets; cable sizing and actuator selection should therefore include a safety margin above the expected 10–40 N operating range. Fourth, unintended lateral movement during actuation remains a risk if socket tolerances are insufficient; precise manufacturing and fit verification during prototyping will be necessary to minimize this. Addressing these failure modes through iterative design and testing will be an essential part of any future validation effort.

Load and Force Requirements

Human finger forces used during everyday tasks can vary considerably depending on the type of activity, object size, and grip motion. Biomechanical studies indicate that functional grip forces for daily living tasks commonly range from approximately 10 to 40 N for precision and moderate grasps, while higher loads are distributed across the entire hand during more demanding activities (17). Additionally, prosthetic hands must be engineered to withstand meaningful grip forces while maintaining structural integrity under load. Moreover, joints must tolerate sufficient torque to permit flexion, extension, and abduction/adduction against object resistance, particularly when manipulating asymmetrical or weighted items. Because prosthetic devices differ from biological tissue in mass and material composition, the torque capacity of the joint must be scaled appropriately to account for mechanical leverage while remaining within safe structural limits. Based on these considerations, the proposed prosthetic design adopts a design target grip force range of 10–40 N, encompassing the range of forces required for common daily tasks while preserving joint stability and mechanical reliability. These figures represent design targets that will need to be confirmed through future prototyping and testing.

Actuation Specifications, Control Interface, and Feedback Requirements

Because the proposed MCP joint has multiple active degrees of freedom, the actuation strategy must achieve coordinated motion without excessive complexity, weight, or cost. One common approach in multi-DOF prosthetic designs is tendon-driven actuation, in which flexible cables routed through the fingers transmit forces from motors or elastic elements to joints, enabling coordinated flexion, extension, and lateral motion while keeping actuators centralized and lightweight (18). To manage complexity, many advanced prosthetic hands employ underactuation, a method in which fewer actuators are mechanically coupled to multiple joints so that fingers can adapt their posture passively to object shapes while still achieving functional grasps (19). Underactuation reduces the total actuator count and power requirements at the expense of fully independent joint control. There is a practical trade-off between using independent actuators, which can offer maximal individual joint control but increase weight, cost, and control complexity, and mechanical coupling or underactuated systems, which require careful design to avoid compromising dexterity. When sizing actuators for the proposed design, expected joint torques based on daily task demands like grasp forces in the range of 10–40 N must be considered to achieve both sufficient torque and joint speed to support functional grasping (19). Several top-of-the-line commercial prosthetic hands balance these requirements by optimizing actuator selection and transmission mechanisms to produce high joint speeds and reliable torque while minimizing overall system mass and power consumption, demonstrating that appropriately scaled actuation can support complex, multi-DOF motion in practical use. These examples suggest that an appropriately scaled actuation system could similarly support the multi-DOF motion of the proposed MCP joint, although this remains to be confirmed through prototyping.

The introduction of multiple DOFs at the MCP joint can specifically increase the complexity of control, particularly given the limited number of user inputs available from an amputee's remaining muscle fibers. Traditional myoelectric systems often rely on Electromyography (EMG) control, which becomes insufficient as joint complexity increases (20). To address this challenge, enhanced pattern recognition and machine learning techniques have been developed to decode EMG signal patterns into commands for multiple coordinated joint motions, allowing more natural and simultaneous control of flexion, extension, and lateral movements. Adaptive or learning-based controllers can further refine signal interpretation over time, improving motion accuracy and responsiveness as the system calibrates to individual muscle activation patterns (4). However, despite these technological advances, effective prosthetic control must prioritize minimizing user cognitive load. As mechanical complexity increases, control strategies must remain intuitive and efficient, with the goal of ensuring that enhanced joint capability does not become mentally fatiguing during everyday use.

Multi-DOF joint architectures also require precise sensing systems to support safe and accurate control. Because our proposed MCP joint allows flexion/extension, adduction/abduction, and potentially passive axial rotation, real-time tracking of joint position would be necessary to maintain stability and prevent unintended motion. One capability that conventional prostheses lack is natural proprioceptive feedback from ligaments and joint capsules; this absence can potentially be addressed by incorporating supplemental feedback mechanisms that may enhance usability. In this case, our proposed design includes a vibrotactile feedback system intended to provide practical sensory cues related to grip force or joint position through vibration, which may help users compensate for reduced biological sensation and contribute to overall control stability.

Evaluation of the Proposed Prosthetic

To evaluate the functional capability of the proposed prosthetic hand and characterize its real-world performance, two standardized tests would be especially valuable: the Prosthetic Hand Assessment Measure (PHAM) and the Box and Block Test (BBT). The PHAM was developed specifically to assess prosthetic function across a variety of tasks, including reaching, grasping, controlling, and the ability to release and grab multiple object types within a consistent framework. Because it records coordinated multi-joint activity, it would allow quantification of the proposed prosthetic's performance, including motion paths, task completion times, and movement strategies (21). In particular, PHAM is well suited for assessing devices with increased DOFs, such as the design proposed here (21). Additionally, the Box and Block Test measures total manual dexterity by recording the number of 1-inch blocks a person can transfer over a partition in 60 seconds, providing a simple yet effective measure of overall hand function with or without a prosthesis (22). The BBT is important for prosthetic research because it provides a straightforward benchmark of how effectively a user can perform repetitive grasp and release actions, even though it does not specifically test multi-axis motion. However, these tests are not without limitations. For example, the PHAM requires a specialized setup and can be time-consuming, and the BBT does not directly measure fine joint coordination or the benefits of lateral motion. Regardless, they provide useful insight into functional performance. By targeting performance on both measures in future testing, we aim to determine whether the increased mechanical complexity of the proposed design can translate into practical, meaningful improvements in everyday hand use without compromising safety or comfort.

CONCLUSION

In summary, this paper examined the limitations of current prosthetic hand technology, especially the widespread use of simplified hinge joints that restrict natural finger motion and reduce dexterity. While advancements such as myoelectric control systems and 3D printing have improved prosthetic accessibility and functionality, the mechanical joint design remains a major constraint. To address this gap, this paper proposes a constrained ball-and-socket MCP joint design that introduces additional degrees of freedom while maintaining mechanical stability. By replicating key aspects of natural hand biomechanics and incorporating controlled motion limits, the design aims to improve grasp adaptability, fine motor control, and overall functional performance while remaining lightweight and cost-effective through the use of additive manufacturing. As this design has not yet been prototyped or experimentally validated, the discussion below presents these potential benefits as motivating hypotheses for future testing rather than as demonstrated outcomes.

The development of a prosthetic joint that more closely matches human finger biomechanics has important implications for the field of prosthetic design and for the daily lives of amputees. Increasing the DOFs at the MCP joint could allow prosthetic users to perform more complex and precise tasks, which could in turn improve independent digit movement and overall quality of life. Additionally, combining this mechanical design with recent control systems, such as EMG pattern recognition and vibrotactile touch feedback, could enable more intuitive and more responsive prosthetic operation. From a wider perspective, integrating anatomical mechanics with scalable manufacturing methods such as 3D printing could make advanced prosthetic hands more accessible and customizable. As a result, this approach has the potential to help bridge the gap between high-performance prosthetic systems and solutions that are affordable and widely accessible to the amputee population.

Future research should focus on prototyping and experimentally validating the proposed joint design through mechanical testing and user trials, which will be necessary to confirm whether the conceptual advantages described above are realized in practice. Performance should be evaluated using standardized assessments such as the Prosthetic Hand Assessment Measure (PHAM) and the Box and Block Test (BBT) to determine whether increased degrees of freedom translate into measurable improvements in dexterity and task performance relative to conventional single-axis designs. Additional work may also explore optimizing actuator placement, improving material durability for long-term use, and refining control algorithms to ensure that the added mechanical complexity remains intuitive for users.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to this work.

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