Quantifying Serviceability: A Maintainability Framework for Tendon-Driven Robotic Hands

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Abstract: ***Tendon-driven robotic hands are widely adopted for their dexterity and affordability, yet their practical deployment is frequently hindered by repair and maintenance challenges. This article introduces serviceability as a core performance metric-alongside force, workspace, and dexterity-by adapting the concept of Mean Time to Repair (MTTR) from reliability engineering into six key performance indicators tailored for tendon-driven hands. A lightweight benchmarking protocol is proposed for evaluating these metrics in lab and classroom settings using basic tools. This framework enables robotic hands to be assessed not only by their capabilities but also by how easily they can be restored to working conditions, making them more reliable for both academic and practical use.***

Keywords: Maintainability, Serviceability, Tendon-Driven Robotic Hands, MTTR, Benchmarking

1. Introduction

Tendon-driven robotic hands have emerged as one of the most versatile and cost-effective strategies for replicating human dexterity. Their appeal lies in their biomechanical similarity to the human hand, affordability compared to fully actuated mechanisms, and adaptability for both research and educational settings. Open-source initiatives have accelerated this trend, making 3D printers increasingly accessible to labs, hobbyists, and classrooms.

This article proposes a maintainability framework for tendon-driven robotic hands by defining serviceability-based KPIs and presenting a repeatable benchmarking protocol to evaluate repair efficiency.

Yet, while published work on tendon hands extensively reports metrics such as grip strength, number of degrees of freedom, joint ranges, and even assembly time, one critical dimension remains underreported: serviceability. Tendon-driven systems are susceptible to wear and failure; tendons fray, knots slip, and tension drifts. Although minor in isolation, they can render the entire hand or finger unusable until they are repaired. In laboratory experiments, this results in hours of downtime; in classrooms, it consumes entire lab sessions, and in assistive or teleoperation contexts, it erodes user trust.

Other industries such as aerospace, automotive, and manufacturing have recognized the importance of maintainability. Metrics such as Mean Time to Repair (MTTR) are standard in equipment assessment, often appearing alongside performance and reliability in reporting protocols. Robotics research has largely overlooked this aspect. While the most advanced hands are praised for their low cost, high dexterity, or anthropomorphic fidelity, they rarely quantify how quickly they can be restored to working order after a tendon failure.

This paper contends that serviceability should become a key performance metric for tendon-driven robotic hands. It introduces maintainability-inspired Key Performance Indicators (KPIs) designed explicitly for robotic hands, along with a straightforward benchmarking protocol to measure them. The paper also highlights design patterns that enhance uptime without compromising dexterity. The aim is to motivate researchers to report serviceability metrics with the same rigor as force or workspace, moving toward hands that are not only dexterous but also practical and dependable in everyday use.

Quantifying serviceability provides a practical means to improve the uptime, reliability, and long-term usability of robotic hands in educational, research, and assistive contexts.

2. Background

In engineering domains where downtime carries significant costs, maintainability is treated as a first-class design requirement. Aerospace, automotive, and industrial systems are routinely assessed not only for performance, but also for how quickly they can be restored to operation after a failure. Formal frameworks, such as MIL-HDBK-472 and IEC 60300-3-10, define maintainability as the probability of restoring a system to operation within a given time frame using prescribed resources [1]. Central to these standards is the Mean Time To Repair (MTTR), which encompasses every stage of recovery: diagnosis, access, repair or replacement, reassembly, and functional verification. MTTR, combined with Mean Time Between Failures (MTBF), determines a system's operational availability:

$$A_o = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \tag{1}$$

This perspective ensures that uptime is characterized as rigorously as peak performance.

By contrast, research into robotic hands has largely prioritized dexterity, force output, and control sophistication while leaving serviceability implicit. For example, the LEAP Hand, developed at Carnegie Mellon University (CMU), emphasizes its low cost and rapid assembly time but provides no repair-time benchmarks [2]. The SoftHand-A demonstrates elegant under-actuation and tactile sensing with minimal hardware, yet omits any maintainability data [3]. Similarly, the ORCA Hand, developed at ETH Zürich, incorporates ratcheting tendon spools and poppable joints to facilitate easy maintenance, yet still reports no quantitative repair metrics [4]. Across these designs, repairability is either assumed or described qualitatively, but rarely quantified in a standardized manner. This omission is especially significant for tendon-driven hands, which are inherently maintenance-intensive. Unlike direct-drive mechanisms, their performance relies on cables, which can stretch, fray, and lose tension, resulting in frequent downtime and maintenance issues. Without formal measures of serviceability, tendon hands can only be meaningfully compared based on capability, not practicality. Drawing from pre-existing maintainability standards, there is a clear case for developing a domain-specific set of indicators, tailored to robotic hands, capturing standard failure modes such as tendon slack or breakage, to quantify how easily these systems can be restored to service.

3. Framework

To adapt maintainability concepts into the domain of tendon-driven robotic hands, the following six Key Performance Indicators (KPIs) are proposed, which map directly to the repair process defined in the MTTR. Each KPI is designed by keeping simplicity, repeatability, and interdependence across labs in mind, while allowing different designs to be compared not only in terms of capability.

Re-string Time (RST)
The most direct metric of maintainability is the time required to replace a tendon and restore it to operational status. RST encapsulates diagnosis, access, repair, and verification in a single measure, aligning directly with MTTR in reliability engineering [1]. For tendon-driven hands used in classrooms or labs, it can reasonably be assumed that an RST of less than or equal to 10 minutes per finger should be considered a baseline target for practical usability.

Tool Changes (TC)
Each additional tool required during repair adds both time and complexity. In aerospace standards, minimizing tool count is a key accessibility requirement [1]. For tendon hands, TC is defined as the number of distinct tools required to perform a tendon replacement. An optimal design should require no more than two standard tools (for example, a screwdriver and a hex key).

Fastener Count (FC)
High fastener counts prolong access time and increase the risk of lost components. FC measures the number of screws or bolts that must be removed and reinstalled during a tendon replacement. Design strategies, such as captive screws or quick-release mechanisms, can significantly reduce this value, thereby reducing the "access" stage of MTTR.

Table 1: Maintainability Card Template to be reported alongside other conventional hand specifications

KPI	Value
Re-String Time (RST)	— min
Tool Changes (TC)	—
Fastener Count (FC)	— Anchor Accessibility (AA) Yes/No
Tensioning Resolution (TR)	— mm/turn Spare Readiness (SR) Yes/No

Anchor Accessibility (AA)
Tendon failures often originate at anchors buried deep within finger housings. AA is a binary indicator of whether the anchor can be accessed without major disassembly. In other industries, accessibility directly drives maintainability scores [1]. For anthropomorphic tendon hands, external clamp anchors or surface-mounted fixtures can turn a one-hour repair into a five-minute task.

Tensioning Resolution (TR)
Precise tendon tensioning is critical; too loose and the accuracy is lost; too tight and friction or premature breakage occurs. TR quantifies the adjustment precision of the tensioning mechanism, expressed as millimetres of tendon displacement per unit turn of a screw, thumbwheel, or ratchet. High-resolution TR reduces the "verification" stage of repair, since tension can be dialled in consistently.

Spare Readiness (SR)
SR evaluates whether tendons can be replaced with pre-prepared spares or require on-the-spot customizations, such as cutting, crimping, or knotting. Systems designed with quick-locking anchors or standardized tendon lengths allow for near-instant replacement, whereas ad-hoc stringing slows down the repair and increases error rates.

Together, these KPIs translate the abstract concepts of maintainability into domain-specific, quantifiable measures. Moreover, they map neatly onto MTTR stages. FC and AA affect access time, while TR and SR affect repair and verification; RST summarizes the full cycle. Including these measures alongside conventional specifications (Degree of Freedoms (DOFs), torque, workspace) would provide a far more realistic account of robotic hand performance in everyday use. Table 1 illustrates one such comparative evaluation.

Mini Benchmark Protocol
For serviceability metrics to be meaningful, they must be measured in a standardized, repeatable, and lightweight manner. Inspired by MMTR procedures in reliability engineering, a simple benchmark task is proposed: replacing a single finger tendon under operational tension. This task reflects one of the most common failure modes in tendon-driven hands while capturing the full cycle of diagnosis, access, repair, reassembly, and verification.

Benchmark Task Definition
A tendon is deliberately released or severed in a controlled manner. The repairer is instructed to restore the finger to its original range of motion and functionality. Timing begins when the repairer picks up the first tool and ends when the finger successfully completes a predefined motion sequence (e.g., full flexion/extension).

Measurement Protocol
a) **Trials:** Perform three repetitions of the benchmark task per hand; report the median value to reduce variability from operator learning.
b) **Operators:** Use at least two different repairers to capture usability beyond a single expert.
c) Metrics Recorded:
- RST: Elapsed repair time (minutes)

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- TC: Number of distinct tools used
- FC: Number of fasteners removed/reinstalled
- AA: Anchor accessibility (Yes/No)
- TR: Tensioning resolution (e.g., 0.5 mm/turn of screw)
- SR: Spare readiness (Yes/No for pre-prepared tendons)

d) **Verification:** Test the repaired tendon against a baseline motion sequence to confirm that the full range of motion and force output is restored.

Reporting Format

Results are summarized in a "Maintainability Card", presented alongside conventional specifications such as DOFs, torque, and grip force. This format enables meaningful, side-by-side comparisons of designs without requiring specialized infrastructure.

The proposed protocol is intentionally minimal, requiring only hand tools and a stopwatch, rather than force sensors, motion-capture rigs, or custom jigs. By treating reparability as a first-order specification, accessible to any lab, this protocol lowers the barrier to adoption. Over time, as more designs are benchmarked, the resulting maintainability data set would support meta-analysis, guiding both researchers and designers toward hands that are both dexterous and sustainable in equal measure.

Serviceability Design Patterns in Existing Hand Designs

While the proposed KPIs define how to measure serviceability, achieving strong scores depends on the mechanical choices made during the design stage. Across recent tendon-driven hands, several recurring design patterns stand out as key enablers of faster and more reliable repair.

External Clamp Anchors

Traditional hands bury tendon knots deep inside finger housings, requiring partial disassembly. By contrast, clamp-style anchors mounted externally allow tendons to be locked or released with a hex key. This improves AA and reduces both FC and RST. The ORCA Hand, for example, uses surface-level routing and quick-adjust tools [4].

Split Covers with Captive Screws

Excessive fasteners slow down access, and loose screws are common hazards in lab settings. Split covers secured with a few captive screws reduce FC and lessen the risk of misplaced hardware. The LEAP Hand demonstrates this approach by minimizing the use of unique fasteners and modularizing access [2].

Ratcheting Spools and Inline Tensioners

Manual knot-tying tends to be slow and inconsistent. Ratcheting spools, as in the ORCA Hand [4], enable predictable tightening in seconds. Inline thumbwheel or screw-based adjusters similarly improve TR, providing quantifiable and repeatable tensioning.

Bowden Cable Routing

Routing tendons through Bowden cables, as in the ADAPT Hand 2 [5], isolates tendon paths from complex geometries and permits re-tensioning from the forearm rather than fingertips. This reduces RST, simplifies calibration, and shields tendons from sharp bends.

These examples demonstrate that serviceability requires conscious prioritization, not radical reinvention. A hand incorporating even some of these patterns may weigh slightly more or cost marginally higher. Still, the resulting reduction in repair time can transform it from a fragile prototype into a practical research and teaching tool.

Material and Standards Considerations. Material selection further influences serviceability. Low-creep fibers such as Dyneema or Kevlar reduce re-stringing frequency compared to nylon. Similarly, structural materials influence the frequency of repairs. Printed PLA links may crack after repeated stress, whereas nylon composites or machined aluminum housings can withstand many more cycles before replacement. Reporting material choices alongside serviceability KPIs would contextualize differences in RST or FC across platforms, clarifying trade-offs between durability, cost, and accessibility.

Finally, lessons from medical devices underscore the importance of maintainability. Prosthetic and assistive systems are already bound by standards (ISO 13485, IEC 60601- 1) requiring sustained serviceability and safety. Extending such thinking to research hands would align academic outputs with real-world expectations.

4. Discussion

Treating serviceability as a performance metric offers both opportunities and trade-offs. The benefits are clear: reduced downtime, improved adaptation in teaching labs, and increased user trust in prosthetics or teleoperation are clear outcomes. Reporting RST or AA alongside DOFs and torque would give future users a more realistic understanding of reliability. In labs, this shift could help prevent abandonment of promising prototypes due to repair fatigue. In prosthetics and robotics, measurable serviceability could directly boost user confidence and long-term use.

On the trade-off side, design features that improve maintainability may add a modest amount of weight, cost, or complexity. Clamp anchors require additional hardware, Captive screws necessitate careful part integration, and Bowden routing can compromise efficiency. Yet, such compromises mirror those in other engineering fields, where reducing MTTR is prioritized for achieving higher overall system availability. A hand that trades a few grams for a reduction in repair time from 45 minutes to 10 minutes is, in practice, more usable.

Importantly, serviceability is not a prescriptive checklist. Different applications warrant different balances: research platforms may tolerate higher FC for novel mechanisms, while teaching platforms should minimize Tool Changes for accessibility. The KPIs provide a framework for reporting, rather than rigid design rules, allowing for comparison across various contexts.

5. Conclusion

Tendon-driven robotic hands are invaluable for advancing dexterous manipulation, yet their deployment is limited by frequent downtime. While specifications such as degrees of freedom, grasp strength, and control fidelity are consistently reported, serviceability is rarely quantified.

This work proposes that maintainability should be treated as a formal performance dimension. By adapting principles from reliability engineering, six serviceability KPIs (RST, TC, FC, AA, TR, and SR) are defined, along with a lightweight benchmark protocol. Future work must focus on systematically reporting these KPIs through figures, maintainability cards, and comparative charts, allowing serviceability to become as standard a specification as DOFs or torque.

We recommend that researchers report a Maintainability Card next to traditional specifications such as DOFs and torque. Doing so would reframe tendon-driven hands from impressive demonstrations into dependable, everyday research and teaching tools. This will essentially bridge the gap between prototype performance and sustainable usability.

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