DTU Autonomous Systems
DTU Elektro

Biomechanical Modeling and Experimental Validation of a Soft Variable-Stiffness Finger Actuation System for Neurorehabilitation

Master Thesis Project Proposal

Contents

1 Project Description

1.1 Background and Task Framing

Parkinson's disease can affect hand function and fine motor control, including the ability to perform repeated voluntary finger movements. These movements are important in everyday tasks and are also relevant in neurorehabilitation training. In the clinical literature, impaired finger tapping is often described through several movement features, including slowness, reduced movement amplitude, altered rhythm, and sequence effect [1, 2].

The finger-tapping literature is stronger in assessment and symptom description than in the design of tapping-specific assistive mechanisms. For this reason, finger tapping is used in this thesis mainly as a rehabilitation-relevant and measurement-rich movement task. The thesis does not aim to develop a full clinical assessment tool or clinical intervention device.

From an engineering perspective, soft actuation is attractive for finger assistance because it can provide compliance and safer physical interaction. Variable stiffness may also affect controllability and the balance between support and mechanical constraint. Therefore, this thesis focuses on a simplified finger-actuator system that can be studied through reduced-order modeling, simulation, and bench-top validation.

1.2 Prior Work and Thesis Positioning

The literature relevant to this thesis can be grouped into three main areas: Parkinson-related finger-movement assessment, finger and hand rehabilitation devices, and modeling or validation methods for simplified actuator-finger systems.

First, Parkinson-related finger-tapping studies provide a useful basis for task definition and measurement. They describe features such as slowness, reduced amplitude, altered rhythm, and sequence effect, and show that these features can be interpreted in more detail than through a single score [1, 2, 3, 4]. These studies are useful for defining rehabilitation-relevant finger motion, but they do not directly solve the design problem of an assistive finger-tapping device.

Second, finger and hand device studies show that simplified, task-specific exoskeletons can be designed around measurable biomechanical interaction variables. Important examples include kinematic compatibility, controlled joint interaction, joint angle measurement, and transferred torque [5, 6]. Other studies show that movement assistance and suppression of unwanted oscillatory motion, such as tremors, can be considered together [7]. However, these mechanical devices do not directly address Parkinson-related repetitive finger tapping.

Third, modeling-oriented studies support the use of simplified but experimentally defensible methods. Reduced-order and quasi-static models can predict useful aspects of finger behavior without requiring full finite-element models [8]. In addition, exoskeleton studies show that bench-top metrics such as range of motion, joint angle estimation, and torque behavior can provide useful evidence for device evaluation at a simplified system level [5, 6].

Taken together, these studies motivate a simplified finger-focused framework that connects rehabilitation-relevant task framing, reduced-order actuator-finger modeling, and bench-top experimental validation. This is the position of the present thesis.

1.3 Problem Statement and Research Questions

Parkinson-related finger impairment is commonly examined using the finger-tapping test. This task can reflect slowness, reduced amplitude, altered rhythm, and sequence effect, rather than only a single speed deficit [1, 2, 3].

Recent literature provides increasingly detailed ways to quantify these motor features. However, most of the direct finger-tapping literature focuses on assessment and symptom effects rather than on tapping-specific assistive mechanism design [3, 4]. This creates a gap between Parkinson-relevant task definition and the engineering of simplified, experimentally defensible finger-actuation systems [6, 5, 8].

This thesis investigates how a reduced-order soft variable-stiffness finger-actuation system can be modeled, simulated, and bench-top validated to study controllability and biomechanical interaction in repetitive finger motion. The main research question is:

> How can a simplified variable-stiffness finger actuator be modeled and validated to study controllable repetitive finger motion?

The following sub-questions help refine the problem:

- Which model parameters strongly affect controllability and actuator-finger interaction?
- Which bench-top validation variables are sufficient to connect actuator behavior to Parkinson-relevant movement concerns such as slowness, amplitude reduction, and movement irregularity?

1.4 Research Goals and Methods

The goal of this thesis is to determine whether a simplified soft variable-stiffness finger-actuation system can be modeled and bench-top validated in a way that is meaningful for rehabilitation-relevant repetitive finger motion. The work also aims to provide engineering insight beyond the current assessment-focused finger-tapping literature.

To achieve this, the thesis will develop a reduced-order actuator-finger model and implement it in a simulation environment, likely using Python. The simulation will be used to study key parameters affecting controllability and biomechanical interaction. The results will then guide the development of a physical mock-up for bench-top validation.

The experimental comparison will focus on measurable variables such as force, torque, range of motion, controllability, repeatability, and robustness. These variables will be considered in relation to Parkinson-relevant movement features such as slowness, amplitude reduction, altered rhythm, and sequence effect. The prototype is intended as a simplified research platform, not as a finished rehabilitation device.

1.5 Practical Considerations and Scope

This thesis is limited to a simplified finger-actuation system developed within the time frame of a Master's project. The work will follow a simulation-first approach. A reduced-order biomechanical model of finger actuation and interaction will be developed first, followed by a physical mock-up for bench-top validation.

A full glove, multi-finger platform, or clinical rehabilitation protocol is outside the scope of this thesis. The thesis does not aim to demonstrate therapeutic efficacy, neuroplastic changes, or clinical outcome improvement. Instead, it focuses on controllability, biomechanical interaction, and experimentally defensible engineering validation.

The simulation and experimental work will focus on measurable variables such as range of motion, force, torque, repeatability, controllability, and robustness. This is consistent with simplified device-validation precedents in the literature [6, 8].

1.6 Learning Objectives

The learning objectives of this thesis are to:

- review literature on variable-stiffness mechanisms, biomechanical finger modeling, soft actuation, Parkinson-related finger motion, and hand rehabilitation devices;
- define functional and experimental requirements for a variable-stiffness single-finger actuation system;
- develop a simplified biomechanical model of a finger-actuator system and analyze it in simulation;
- design and implement a mock-up finger-actuator prototype for experimental validation;
- characterize and evaluate the prototype through simulation and bench-top experiments;
- analyze the system and identify directions for future neurorehabilitation research.

2 Project Plan

2.1 Deliverables

Table 2.1: Project deliverables.

#	Title	Description	Type	Target
D1	Project Plan	Final version of the project proposal and plan.	Report	W5
D2	Reduced-Order Model Baseline	Initial reduced-order finger model and simulation framework.	Modeling	W10
D3	Prototype v1 and Bench-top Setup	First working mock-up and initial validation setup.	Prototype	W15
D4	Experimental Comparison Results	Initial comparison between simulation and bench-top measurements, including data processing and analysis.	Study	W19
D5	Final Thesis	Final written thesis report for submission.	Report	W21

2.2 Milestones

Table 2.2: Project milestones.

#	Title	Description	Target
M1	Project scope locked	Project description, scope, and initial plan agreed upon.	W5
M2	Baseline simulation operational	Reduced-order finger model implemented and running in simulation.	W10
M3	Validation strategy finalized	Validation variables and experimental approach defined.	W12
M4	Prototype concept frozen	Mock-up concept selected for implementation.	W12
M5	Bench-top system operational	Prototype, instrumentation, and initial setup assembled and functional.	W16
M6	First comparisons completed	Initial comparison between simulation and experimental measurements completed.	W19
F	Thesis hand-in	Final thesis submitted.	W22

2.3 Gantt Chart

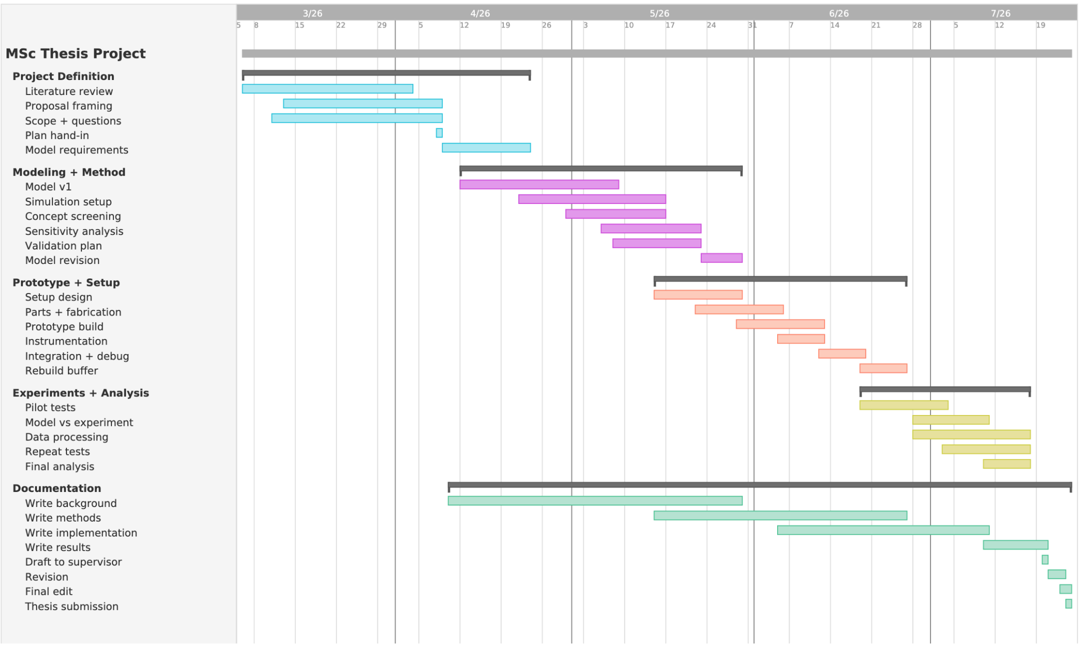

Figure 2.1: Gantt chart for the planned thesis activities and milestones.

2.4 Activities

Table 2.3: Project activities and work packages.

#	Title	Description	Phase
1	Literature review	Review literature on Parkinson-related finger motion, soft actuation, variable stiffness, finger biomechanics, and rehabilitation devices.	Preliminary framing
2	Problem formulation	Refine research questions, scope, validation variables, and requirements.	Preliminary framing
3	Reduced-order modeling	Formulate and simulate a simplified finger-actuator model.	Modeling
4	Parameter analysis	Study how key model parameters affect system behavior.	Modeling
5	Mechanism concept selection	Select a variable-stiffness mock-up concept.	Mock-up
6	Prototype implementation	Build the finger mock-up and validation setup.	Mock-up
7	Experimental validation	Perform bench-top measurements and compare them with simulation outputs.	Experiments
8	Result analysis	Analyze the model, mock-up, and experimental comparison.	Experiments
9	Thesis writing	Write and revise thesis chapters throughout the project.	Thesis writing
10	Final editing and submission	Complete final proofreading, formatting, and submission.	Thesis writing

2.5 Risk Analysis

The main risks of the project are summarized in Table 2.4. Risk levels are indicated on a scale from 1 to 5, where 1 represents low risk and 5 represents high risk of delay or reduced technical outcome.

Table 2.4: Risk analysis.

#	Title	Risk	Mitigation	Level
R1	Late concept selection	Too much time may be spent comparing actuator concepts or model variants.	Select one baseline concept early and treat alternatives as secondary.	4
R2	Weak validation setup	The bench-top setup may not support a clear comparison with the model.	Define validation metrics early and design the setup around them.	4
R3	Parameter uncertainty	Some model parameters may be difficult to estimate reliably.	Keep the model low-order and focus calibration on the most influential parameters.	3
R4	Limited benefit of variable stiffness	The study may show only a small advantage of variable stiffness.	Frame the thesis as a comparative investigation rather than as a proof that variable stiffness is always better.	3

Bibliography

[1] Matteo Bologna et al. “Evolving Concepts on Bradykinesia”. In: *Brain* 143.3 (Mar. 1, 2020), pp. 727–750. DOI: 10.1093/brain/awz344.

[2] Giulia Paparella et al. “Analyzing the “Bradykinesia Complex” in Parkinson’s Disease”. In: *Movement Disorders* 41.1 (Jan. 2026), pp. 143–155. DOI: 10.1002/mds.70082.

[3] Javier Amo-Salas et al. “Computer Vision for Parkinson’s Disease Evaluation: A Survey on Finger Tapping”. In: *Healthcare* 12.4 (Feb. 8, 2024), p. 439. DOI: 10.3390/healthcare12040439.

[4] Tahereh Zarrat Ehsan et al. “Interpretable and Granular Video-Based Quantification of Motor Characteristics from the Finger-Tapping Test in Parkinson’s Disease”. In: *npj Parkinson’s Disease* (Mar. 8, 2026). DOI: 10.1038/s41531-026-01307-w.

[5] Ning Sun, Guotao Li, and Long Cheng. “Design and Validation of a Self-Aligning Index Finger Exoskeleton for Post-Stroke Rehabilitation”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 29 (2021), pp. 1513–1523. DOI: 10.1109/TNSRE.2021.3097888.

[6] Emanuele Peperoni et al. “Self-Aligning Finger Exoskeleton for the Mobilization of the Metacarpophalangeal Joint”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 31 (2023), pp. 884–894. DOI: 10.1109/TNSRE.2023.3236070.

[7] Andong Yi et al. “A Hand Exoskeleton with Linear Motors (HELM) for Pathological Tremor Suppression of Fingers”. In: *Intelligent Sports and Health* 1.2 (Apr. 2025), pp. 86–97. DOI: 10.1016/j.ish.2025.03.002.

[8] Lucas Gallup, Mohamed Trabia, and Brendan O’Toole. “Predicting the Response of a Tendon-Driven Prosthetic Finger with Hyperelastic Joints”. In: *Results in Engineering* 27 (2025), p. 106979. DOI: 10.1016/j.rineng.2025.106979.