

# Experimental Modeling and Compensation of Torque Loss in a Cable-Driven Elbow Exoskeleton Using Structural Optimization

by

Adilet Toleshev

Submitted to the Department of Robotics Engineering  
in partial fulfillment of the requirements for the degree of

Master of Science in Robotics

at the

NAZARBAYEV UNIVERSITY

Apr 2026

© Nazarbayev University 2026. All rights reserved.

Author .....

Department of Robotics Engineering

Apr 29, 2026

Certified by .....

Aibek Niyetkaliyev

Associate Professor

Thesis Supervisor

Accepted by .....

Yelyzaveta Arkhangelsky

Dean, School of Engineering and Digital Sciences

# Experimental Modeling and Compensation of Torque Loss in a Cable-Driven Elbow Exoskeleton Using Structural Optimization

by

Adilet Toleshev

Submitted to the Department of Robotics Engineering  
on Apr 29, 2026, in partial fulfillment of the  
requirements for the degree of  
Master of Science in Robotics

## Abstract

Upper-limb rehabilitation exoskeletons frequently install remote cable-driven actuation to reduce distal mass and improve comfort for patients. Bowden cables are suitable for such systems due to their ability to transmit force through complex path. However physical effects like friction, hysteresis, slack, and backlash cause difference between motor and joint torque. These effects mitigate control accuracy and make interaction less predictable. Most of existing research focus on local friction of cable or assume that cable is mechanically fixed. Consequently, the impact of whole cable routing geometry on torque transmission remains insufficiently explored in antagonistic cable systems. This study experimentally examines torque loss in antagonistic Bowden cable-driven exoskeleton systems. Torque transmission is evaluated from different cable routing using load cells and angle encoder. Using the experimental results, mathematical structure-dependent is developed to predict torque loss based on cable routing geometry and operational conditions.

Thesis Supervisor: Aibek Niyetkaliyev

Title: Associate Professor

## Acknowledgments

I would like to express gratitude to my thesis advisor, Prof. Aibek Niyetkaliyev, for his support throughout this research. I would also like to thank doctoral researcher Sharafatdin Yessirkepov for his assistance in assembling the prototype and helping with the experimental setup.

# Contents

|          |                                                              |           |
|----------|--------------------------------------------------------------|-----------|
| <b>1</b> | <b>Introduction</b>                                          | <b>7</b>  |
| <b>2</b> | <b>Related works</b>                                         | <b>11</b> |
| <b>3</b> | <b>System overview and Mechanical Design</b>                 | <b>21</b> |
| 3.1      | Overall System Architecture . . . . .                        | 21        |
| 3.2      | Mechanical Structure of the Elbow Prototype . . . . .        | 22        |
| 3.3      | Bowden Cable Actuation System . . . . .                      | 23        |
| 3.4      | Cable Routing Configurations . . . . .                       | 24        |
| 3.5      | Sensors and Instrumentation . . . . .                        | 25        |
| 3.6      | Data Acquisition and Control Hardware . . . . .              | 25        |
| 3.7      | Theoretical reference model . . . . .                        | 26        |
| <b>4</b> | <b>Experimental protocol</b>                                 | <b>29</b> |
| <b>5</b> | <b>Experimental Results and Torque Loss Characterization</b> | <b>31</b> |
| <b>6</b> | <b>Discussion</b>                                            | <b>36</b> |
| <b>7</b> | <b>Future directions</b>                                     | <b>38</b> |

# List of Figures

|     |                                                                                       |    |
|-----|---------------------------------------------------------------------------------------|----|
| 1-1 | Example of a cable-driven upper-limb exoskeleton with remote actuation.[10]           | 8  |
| 1-2 | Force transmission in a Bowden cable system [8]                                       | 8  |
| 3-1 | Extended elbow                                                                        | 24 |
| 3-2 | Different Bowden cable routing configurations (1–6)                                   | 25 |
| 3-3 | Matlab simulation model, where blue line - upper moment arm, green - lower moment arm | 26 |
| 3-4 | Moment arm vs. time                                                                   | 27 |
| 3-5 | Moment arm vs. angle                                                                  | 27 |
| 3-6 | Angle encoder AMT102-V                                                                | 28 |
| 3-7 | Tension sensor MLS66                                                                  | 28 |
| 3-8 | Matlab control scheme                                                                 | 28 |
| 5-1 | Raw and smoothed torque                                                               | 32 |
| 5-2 | Force vs time (biceps and triceps)                                                    | 33 |
| 5-3 | Motor 1 torque vs angle comparison                                                    | 33 |
| 5-4 | Motor 2 torque vs angle comparison                                                    | 34 |
| 5-5 | Net motor torque comparison                                                           | 34 |
| 5-6 | General joint torque comparison                                                       | 35 |

# List of Tables

|     |                                                              |    |
|-----|--------------------------------------------------------------|----|
| 5.1 | Comparison of angles with and without force sensor . . . . . | 31 |
| 5.2 | Motor torques for different configurations . . . . .         | 32 |

# Chapter 1

## Introduction

Rehabilitation of upper limb functionality is one of the most important tasks of health-care, especially for patients who were diagnosed with stroke, neurological disorders and musculoskeletal injuries. Such kind of impairments significantly limits the elbow range of motion and in many case require long-term recovery [1]. As the result, robotic rehabilitation technologies have been developed to provide predictable, accurate and measurable assistance in recovery process. Among different inventions wearable exoskeletons have received attention because of ability to support human motion while being portable and safe [2]. Within upper-limb the elbow joint is an important part. It takes part in various movements such as reaching, lifting or pushing objects. Despite having only one-degree-of-freedom, developing wearable robot for this joint remains difficult task. For such kind of systems torque delivery accuracy is required to provide both effective rehabilitation and safe interaction with patient [3]. Excessive torque can result in comfort absence or even bone injury, whereas torque deficiency will diminish the rehabilitation benefit. Therefore, precise and highly predictable torque near joint is an important requirement for medical exoskeletons. In order to reduce mass and inertia which could be applied directly on patient arm, remote actuation system was developed for exoskeletons. In these systems actuators are positioned at some distance from the joint and motors transmit power through flexible elements like cables [4]. Among various types of cables, Bowden cable stands out. Their frequent usage is dictated by its characteristics such as low weight, flex-

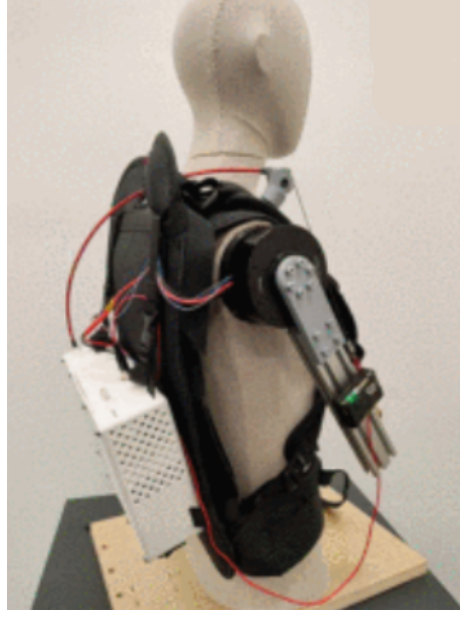


Figure 1-1: Example of a cable-driven upper-limb exoskeleton with remote actuation.[10]

ibility, and ability to redirect force through complex trajectory [5]. This approach is quite useful and effective for elbow exoskeletons because distal mass is important for patient's comfort and safety. However, each force transmission system has its own disadvantages, and Bowden cable system is no exception. Bowden cables introduce significant nonlinearities into system thereby skewing relationship between motor torque and joint torque.

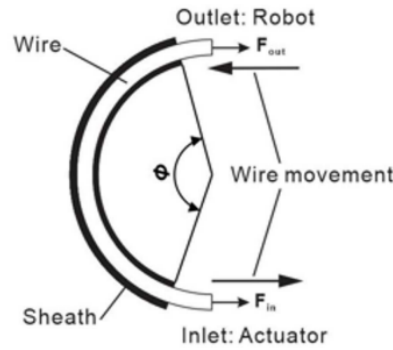


Figure 1-2: Force transmission in a Bowden cable system [8]

In a Bowden cable system, there are several reasons of energy loss and hysteresis during force transmission, such as friction between cable and sheath, cable bending,

slack and backlash [6]. Thus, torque generated by the motor often does not align with the torque experienced by elbow joint. These effects are significantly evident in antagonistic cable systems, where two cables act in opposite directions to provide accurate flexion and extension [7]. Constant direction changes in antagonistic systems intensify nonlinearities. Dead zones and asymmetric behavior [8] take place and lower control accuracy. Consequently, Bowden cables make exoskeleton design lightweight and comfortable for patients, whereas they make the system harder to control due to low torque accuracy.

Torque precision is a critical factor in rehabilitation exoskeletons. Many existing control strategies assume that torque generated by motor is transmitted to joint without losses. In practice, this premise does not correspond to real cable-driven mechanics, causing lowered torque accuracy, unpredictability during direction change and inconsistency in interaction [9]. Previous research has raised questions of Bowden cable behavior, including friction modelling and hysteresis characterization. Several classical friction models that are used to describe cable behavior, which include Coulomb, Stribeck, and LuGre models. Despite these models cover particular nonlinear effects, they are basically used for local parts of cable and they don't account for long length routings geometry [10]. Other studies have explored cable routing thereby proved that curvature and bending angles have impact on force transmission. However, these research use cable tension sensors for measurement or motor current, but do not utilize direct joint torque measurement [11]. Accordingly, numerical correlation between cable routing and real joint torque loss continues to be limitedly explored. Moreover, most of explored approaches account only fixed cable configurations and do not research how cable route changing during force transmission affects torque loss in antagonistic system. Complex influence of geometry, friction, slack and backlash on actual joint torque has not been fully explored. Consequently, there are a few methods that can include mechanical cable geometry with torque loss in terms of design control. This gap reduces predictability, stability and therapeutical benefits of cable-driven elbow exoskeleton.

The aim of this thesis is to address this gap by conducting experiments and analyt-

ically investigate structure-dependent torque losses in Bowden cable-driven antagonistic system. First, it is planned to quantify torque loss, which depends on mechanical routing, using angle and force measurement sensors, installed on full-scale arm prototype. Second, simple structure-dependent torque loss model is developed, which includes the effects of routing geometry, velocity, weight of the arm, and transmission nonlinearities like slack and backlash. After all, the proposed model is validated on new untested cable configuration to estimate its predictive capability. Finally, verified model is used in one of the cable routings and motor torque is adjusted in accordance with model prediction to reach desired elbow angle.

This thesis provides three main contributions. First, an experimental framework is demonstrated that can quantify joint torque loss in Bowden cable-driven antagonistic system. Second, parametric mathematical model that can link mechanical routing geometry with working conditions to torque loss. Third, the impact of structure-dependent torque loss compensation on simple current control strategy, which highlights the importance of system design that accounts for routing geometry and control strategies. The remainder of this thesis is organized as follows. Chapter 2 reviews related works on cable-driven systems, Bowden cable physical effects, antagonistic system behavior and torque transmission. Chapter 3 presents mechanical design of the whole arm prototype and layout of sensors. Chapter 4 describes experimental protocol and investigates torque losses during transmission in various routing configuration. Chapter 5 introduces mathematical model which take into account effects of geometry, load and operational conditions. Chapter 6 presents discussion of results obtained from experiments and their implication for cable-driven robotic systems. Chapter 7 summarizes all findings, highlights contributions and suggest probable research areas for future studies.

# Chapter 2

## Related works

The elbow joint plays significant role in arm motion independence by providing hand position in reachable space during activities of daily living (ADLs). Movements such as reach-to-mouse, objects lifting, feeding and other objects manipulations require coordinated shoulder-elbow interaction rather than simple one DOF elbow joint motion. Therapeutical comparisons between task simulated in laboratory conditions and real-world ADLs present that usually simplified movements require better and more realistic kinematic demands for elbow-shoulder complex [12]. This proves that upper-limb functionality must be estimated under conditions close to real. Motor impairments often lead to elbow joint range of motion (ROM) limitations. This does not only appear in comfort reducing, but also in coordination between joint and compensatory trunk strategies. Complex kinematic research of various ADLs motions demonstrates that quality and comfort of upper-limb movement deteriorate because of reducing of elbow extension ability, increasing time for task completion and abnormal coordination between shoulder and elbow joints [13]. One of the most extensively studied arm motor impairment is stroke, which clearly demonstrates clinical significance of constant elbow disfunction and its influence to long-term arm motion limitation [14]. Although stroke illustrates usual reference condition, similar limitations of functionality also happens after orthopedic injuries, post-surgical stiffness and constant muscle weakness. Even people without neurological disorders lifting and repetitive arm movements create significant mechanical load and thereby proves

relevance of mechanic assistance for elbow joint [15]. In neurological contexts which involves spasticity and deteriorated motor control, stiff directed mechanical assistance may be inappropriate. Studies of powered upper-limb exoskeletons demonstrate that controllable and task dependent assistance increase efficiency of movements simultaneously keeping patient able to take efforts during help [16]. Complexity of joint elbow participation in various movements tangles engineering solutions. Kinematic research shows that each phase of movements, for instance distal reaching or proximal transmission, is characterized by stable but task-dependent pattern of coordination [12, 13]. These results point out assistance strategies that have to account for multi-joint dynamics, not only fixed trajectories. Experimental studies of passive and active exoskeleton systems emphasize that torque provided assistance must be stable, predictable, well controllable and coincide with physiological joint constraints to avoid excessive load and undesired response movements [16, 17]. Understanding of these clinical, biomechanical observations and converting them into engineering requirements leads to highlighting several key principles. Mass and inertia of distal elements have to be minimized because additional load on forearm causes compensatory movements and disrupts natural coordination patterns [13, 15]. Safety mechanisms have to provide controllable range of motion and predictable torque [16, 17], whereas assistance have to be adjustable and repeatable to adapt to different impairment level and particular task requirements [16]. In addition, objective measurability is important. Clinical validation of exoskeleton efficiency has to rely on quantifiable parameters such as range of flexion and extension, task completion time, peak velocity and smoothness indicators which allow to gain objective assessment of efficiency [13]. Collectively, research results in field of rehabilitation biomechanics and assistive technologies converge to main principle – efficient assistance is provided not only by actuator, but also by reliable torque transmission to joint and its measurable impact on completion of ADLs. These biomechanical requirements directly influence engineering solution for rehabilitation devices, particularly device architectures.

Development of upper-limb exoskeleton is driven by necessity of finding balance between accurate torque delivery, mechanical rigidity and comfort for patient. On

early stage of rigid exoskeleton main emphasis was on joint kinematic precision and torque predictability, which was provided by mechanically constrained linkages. As indicated in systematic review [18] rigid architecture allow precise aligning of axis, manageable joint stiffness and reliable torque delivery what is main condition for repeatable rehabilitation process. However, placing of actuators directly on limb increases distal mass and inertia and negatively impacts on dynamic parameters and patient comfort, especially in rehabilitation conditions when patients are not able to take muscle effort. To overcome these limitations soft wearable exoskeletons were developed. Textile based and compliant systems reduce construction mass and improve ergonomic for patient's body [19]. Disposal of rigid linkages and frames in such kind constructions diminish inertia and make wearing more comfortable. However, absence of rigid, but predictable mechanical transmission makes new technical challenges for developers. Deformation of soft elements during movements complicates precise assessment of torque on motor and on joint. In results soft systems create comfort while sacrificing predictable torque delivery. Neutral solution for rigid and complaint constructions was found in systems with remote actuation. In such kind of systems actuators are placed at some distance from limb joint and torque is transmitted using cable mechanisms. As it is shows in proceeding [20], upper limb cable-driven exoskeletons have been in demand for rehabilitation due to ability of redistribute mechanical system mass with keeping torque delivery active. Placing motor on different places like torso or in backpack modules it is possible to reduce distal inertia without losing system controllability. Practical implementation of this concept is presented in CURE [21] where three degrees-of-freedom such as flexion/extension, pronation/supination and wrist flexion/extension is carried out by using cables. Experimental check revealed tracking errors below  $3^\circ$  (RMSE) that proves possibility of assisting joint with distantly placed actuator and cable transmission, which reduced load on the limb. These findings are evidence that remote actuator is rational architectural solution. However, replacing of actuators leads to one important problem – torque transmission along cable routing. Comparing with rigid mechanical linkages, cable-driven systems largely depend on geometry of routings. In research [22], it is illustrated that cable

routing causes movements of several joint even if they are not connected. Therefore, this behavior requires decoupling matrices to analyze kinematic of joint solely. This work emphasizes that geometry of the cable affects to transmission characteristics. However, focus is still on kinematic decoupling rather than systematic quantification of torque loss. Besides kinematic coupling, nonlinear effects take place due to friction in Bowden cables. Experiments [8] shows delivering torque exponentially depends on bending angle, which was described in capstan equation. Changes in bending angles significantly affect on output torques. Consequently, there is need of compensatory strategy to diminish friction-induced energy loss. It is important to note that in these studies authors mostly focus on compensation within control but not structural design. They do not investigate torque loss as function of whole cable routing geometry. Exoskeletons evolved from rigid system to soft ones, where remote actuation obviously demonstrates tendency of reducing mass and inertia on limbs. Furthermore, in this engineering solution torque delivery is still efficient. Despite existing friction models and compensation approaches, there is no systematic analysis of torque loss in cable-driven exoskeletons which would account for structural design. This unresearched gap is basis for developing of new torque delivery model which has geometric parameters affecting actual torque delivered to joint. Bowden cables are appropriate solution for torque transmission.

Cable transmission has become of the wide-used solution for rehabilitation systems as it allows placing of actuators away from limb with keeping ability to generate torque. Frequently used cable-driven exoskeletons formalize geometric connection between joint rotation, cable translation and output torque thereby showing tension force is converted in assistance in rehabilitation devices [9]. Likewise, restoration therapeutic systems devoted for home usage utilize remote cable transmission for reducing distal mass and comfort improving during ADLs. However one important factor is not usually described – torque generated by motor may not be equal to torque delivered to joint [21]. By this separation between motor torque and actual joint torque transmission layer is revealed, whom physical behavior has to analyzed. In architectures with distant actuators Bowden cables appear to be suitable due to its flexibility and

compact sized on arm. These features are reached because of placing steel cable inside rubber sheath. However, advantage like flexibility causes disadvantage like full dependence on configuration. Experimental research on remote actuation systems with Bowden cables demonstrates energy loss with bending angle increasing. This directly coincides with capstan friction model dependencies [5]. Therefore, considering torque transmission as a constant gain is inappropriate approach because torque becomes a function of geometry. Thus, cable routing becomes as an adjustable variable directly affecting on torque delivery to joint. Once routing is treated as structural parameter, then changes in cable length, curvature, attachment points and guide location obtain mechanical significance. Studies on soft exoskeletons for upper-limb with using Bowden cables revealed that changes in cable location and methods of attachment leads to change of interaction forces and upper-limb respond [23]. Although these results include discussion about ergonomics and assistance efficiency, they also reveal hidden finding: topology of routing may affect effective physical behavior of actuator at joint. These factors become more meaningful when it comes to antagonistic configurations with Bowden cables. These systems provide two-directional motion of joint and control stiffness due to cable pretension from both sides. Even if two cables slip along different paths during motion, their energy loss may differ even under symmetrical control commands. Experimental works on antagonistic cable-driven robotic systems with Bowden cables demonstrates influence of bend radius, cable symmetry, routing geometry on stability of transmission and precision [24]. Consequently, routing asymmetry may cause unequal torque delivery between two paths and deteriorate controllability. Torque measurement and assessment inseparably connected to this physical effect. Because friction, compliance and backlash take place along cable path, the actual joint torque may not correspond to initial motor torque. This limitation is described in Bowden-driven SEA-based hand exoskeletons, where for accurate torque assessment of joint backlash modelling is necessary [25]. Similarly, embedded sensors are designed to track parameters along path and allows to compensate hysteresis [26]. Nevertheless, even applying compensatory strategies transmission still depends on geometry of routing and load conditions. In total, cable systems based

on Bowden cables are lightweight and practical solution for rehabilitation, especially for antagonistic configurations. However, efficiency is mostly defined by transmission characteristics depending on geometry. With routing change torque changes. This structural feature creates engineering challenge for Bowden cable exoskeletons and raises question of developing structure-dependent characterization.

The nonlinear behavior with Bowden cable is considered as key challenge in remote actuation systems. For upper-limb exoskeletons with Bowden cables, relationship between actuator and joint torque is affected by factors such as friction, hysteresis, sheath compliance and bending angle. These factors skew relationship. Detailed research on mechanics and friction in cable-driven exoskeleton demonstrated that even under controlled geometry of cable routing, delivering force is experiencing effects of hysteresis and offset, which cannot be described by Coulomb–viscous models [27]. Authors showed that friction depends on pretension of cable and cable routing configuration. This fact proves that Bowden cable based systems should be considered as non-ideal channel of force transmission, but nonlinear whose physic response is defined by configuration in space. Besides static friction models, dynamic approaches exist, which illustrates curvature of cable and deformation of its sheath can affect cable tension on different parts of path. Dynamic model of cable-conduit actuator for interaction task accounts for effects of curvature and proves tension hysteresis take place under different cable routings [28]. In their model transmission efficiency directly depends on geometry of routing. This fact emphasizes bending angles together and local curvatures influence tension of cable at the end of path. Important to note that authors highlighted idea that even configuration changes without any control parameters altering can cause mismatching of input and output force. Geometric influence of bending angles is described by capstan equations, according to which tension ratios depend exponentially on wrap angle. Experimental research of two cable Bowden system showed that force transmission efficiency reduces with growing of accumulated wrap angle thereby proving exponential dependency [29]. Comparably, experiments with loop-routing presented that changes in only transmission trajectory led to change of requirement for friction compensation. In addition, transmission effi-

ciency significantly depends on curvature of trajectory [30]. These studies collectively show cable routing is question of systems layout, but also is a key factor that defines mechanical transmission. Although some works have focused on friction compensation with tension modelling, much fewer addressed actual joint torque in form relevant for exoskeletons actuation. Recent study on double-cable system with sheath for exoskeleton suggested one of the detailed formulas of relationship between curvature, pretension, hysteresis with joint torque [31]. By including curvature integrals, authors conducted experimental validation of output torque with altering geometry of routing thereby modelled transmission which account for cable path. Nevertheless, suggested analysis was not formed as systematic comparison between full cable path with actual torque delivered to joint. Moreover, research was not conducted on antagonistic cable system for elbow joint. On the whole, presented studies demonstrated that transmission based on Bowden cables is characterized by nonlinearity which caused by friction hysteresis, tension reducing and curvature of cable path. Routing geometry has noticeable impact on force transmission and dynamic models let approximately describe force skew. However, in rehabilitation robotics joint assistance is carried out not only by cable tension, but torque delivered to the joint. Since joint torque is defined not only by tension, but also effective moment arm which is measured by angle, current friction models based on force are incomplete. Elbow rehabilitation exoskeletons with antagonistic cable system are special architecture in which asymmetry in cables and upper-limb position in space complicates finding ratios between motor and actual torque. Consequently, lack of analysis exists, which includes geometry, tension distribution, bend angles and moment arm. These factors are crucial for rehabilitation which requires safe and accurate motion.

Cable-driven exoskeletons provide low distal mass due to remote actuation. However, this advantage raises the fundamental issue: torque delivered to joint ceases to be result of motor torque and start to be dependent of routing geometry, friction and tension. Therefore, problem of torque transparency became inseparable from mechanical behavior of cable system itself. Research on torque measurement extracted from interaction between human and exoskeleton cable systems reveals that installed

torque sensors give only approximate values. Authors suppose that accurate torque estimation would require taking whole mechanical chain into account, and cannot be based only on motor side [32]. This underscores, torque accuracy limited by inner mechanics of transmission itself. Transmission architecture additionally defines these restrictions. Comparison between pulley and Bowden transmissions exemplify that Bowden cable systems provide better routing flexibility, but also is a source of high friction and hysteresis. These factors directly decrease transmission efficiency and controllability [33]. As the result, torque loss is consequence not only friction but is architectures' feature. Tension loss under external and inner loadings reinforces this point of view. Research on tendon-driven systems demonstrates that effective tension on distal end changes with mechanics configuration and load distribution thereby torque delivery become dependent from system state [34]. This sensitivity to configuration especially observable in Bowden cable system where friction reveals nonlinear and hysteresis behaviour depending on curvature and transmission direction [35]. In antagonistic exoskeletons with double cable actuator asymmetry of friction and cables interaction complicates torque generation. Results of modelling represents that actual delivered torque is defined by interaction between two cables and their friction characteristics with direction, that lead to asymmetrical behaviour of torque [36]. Collectively, these studies shows that torque delivery in cable-driven exoskeletons is formed by factors such as: system architecture, friction distribution, tension loss and antagonistic interaction. Therefore, for generation of necessary accurate torque, systematic modelling of whole transmission chain is required, not only local parts.

In all analysed studies one tendency can be observed. Research in field of upper-limb rehabilitation shows that effective assistance for elbow must maintain natural motion coordination, minimize inertia of distal linkages and provide torque which can be measured. Next, architectural works illustrates that system with remote actuation is intermediate solution between stiff structure and soft elements. By replacing actuators from limb to back, such systems minimize inertia while saving possibility of torque generation. However, this engineering solution introduces intermediate transmission level (cables), whose mechanical behavior is defined by torque reached

the joint. Following studies on Bowden cable exhibits transmission element cannot be considered as ideal conduit. Hysteresis, friction, tension loss, pretension sensitivity together converts input torque to output actual torque which depends on configuration. Capstan equation and dynamic “cable-sheath” models support geometry influence on delivered tension. Experimental research also establishes that only change in configuration without altering control command is able to distinction in delivering torque. In antagonistic systems these effects become more critical: routing asymmetry, curvature change during movement and friction distinction in both cables may violate balance in joint. At the same time, studies dedicated to torque estimation and compensation reveals one limitation. Although friction models, feedforward strategies and reconstruction methods based on sensors improve control accuracy. Mostly, they assume pre-determined or unchangeable transmission behavior. Frequently, analysis is focused on tension modelling, not on actual joint torque. However, in rehabilitation robotics joint assistance is not defined by proximal cable tension, but torque relatively to elbow, which simultaneously depends on delivered torque and arm moment, defined by geometry. When geometry of cable routing changes with pose, relationship between motor torque and actual joint torque become dependent on system state. Despite extensive work of friction modelling, analysis of cable routings and antagonistic systems in literature still lacks systematic description of torque delivery as a function of full geometry. Existing models often validates only specific configurations or consider transmission from force point of view. They do not unify knowledge of routing curvature, antagonistic cable asymmetry and angle arm moment. In results, distinct quantitative relationship between configuration and energy loss in joint during motion remains insufficiently researched. This unexplored gap defines main idea of this thesis. Instead of treating transmission effect as secondary disturbance requiring control compensation, in this thesis torque transmission itself is main analysis object. By developing full scale elbow prototype, experimentally researching torque transmission under different configurations and formulating mathematical model, which depends on geometry of routing and making relationship between routing and energy loss. This work is directed for understanding how listed factors influence actual assistance.

Such kind of characteristics are necessary for accurate torque generation, future construction optimization and control strategies relying on proved physical behavior. In this way, this thesis raises unaddressed question of relationship between mechanical architecture and actual torque delivery in antagonistic cable-driven exoskeletons using Bowden cables and presents quantitative, experimentally proved characteristics of torque.

# Chapter 3

## System overview and Mechanical Design

### 3.1 Overall System Architecture

The system on which all experiments are conducted is full-scale arm prototype. Prototype mimics natural human elbow joint rotation. The general degrees of freedom is 1. In order to rotate elbow through axis Bowden cables are utilized from both arm sides: upper and lower sides. This cable configuration is called antagonistic cable system. It allows hand to be more controllable. In prototype remote actuation principle was implemented to reduce distal mass and inertia. General arm prototype was designed to copy backpack motor placement. To simplify building process prototype assembly wooden support was developed. Motors placement holders are designed with spool for cable winding. Angle of elbow flexion and extension is counted by angle encoder. Motors rotate in same direction both in flexion and extension phase. Motors are required to pull cable by twisting which depends on phase of motion. Antagonistic motion is provided by simultaneous motor rotation with different speed in both directions. Cables are wound on cable drum with helical groove to make cable behavior while tension more stable and predictable. Different cable routing were developed for elbow prototype, so anchoring points and sheath length vary with configuration number. Three types of sensors are used on prototype: force sensors, angle encoder

and embedded motor hall sensor. Encoder is placed on elbow rotation axis to detect any elbow movement. Force sensors are placed at the end of cable routing to account final tension of cable on forearm. Embedded motor hall sensors detect current level inside motor giving control on motor rotation speed. Escon motor controllers board is utilized for precise motor control. Encoder and motor controllers are connected to Data Acquisition Board which directly connect control scheme in Simulink software with physical prototype.

### 3.2 Mechanical Structure of the Elbow Prototype

The artificial arm consists of several part such as upper arm segment, forearm segment and elbow hinge joint. The distance between elbow joint and forearm ending is 25 centimeters. Distance between elbow joint and upper arm end (shoulder) is 30 centimeters. Elbow joint consists of metal rod which is fixed to forearm to follow forearm rotation. On the same rod encoder is located. It's aim is to obtain angle data of forearm and send data to Data Acquisition Board (DAQ). Behind the arm two motors are attached. They rotate to carry out cable translation. Motor are fixed due to bolted connection motor holders. Arm is attached to plastic support which serves as link between wooden support and arm. To experiment conduction convenience support was developed in 1 meter height. with In figure only one cable routing was illustrated. On the arm shoulder mimicking part was glued. It is important as it creates plain surface for future anchoring points. The end of forearm is equipped with two cable hooks for upper and lower cables. Near these hooks force sensors are attached, but in several configuration force sensors placement can be altered. All cable configurations vary and geometry is not same, but all configurations has anchoring point where cable sheath can be begins or ends, in doing so making sheath fixed and stable. In order to mimic real human forearm filler was added inside forearm so it's weight reached 984 grams, which is two times lower than real 1,7 kilograms weight. Forearm construction implies real flexion movement, so technical hollow was designed near elbow joint. Actual range of motion of elbow prototype is 135 degrees, which

corresponds to average flexion motion of real human. In opposite, prototype is able to extend reverse on 4 degrees. All arm components were printed using PLA plastic via 3D printed, except wooden support. Plastic details have different level of infill density depending on purpose during actuation. Cable sheath consists of rubber and thin dense flexible plastic covering inside black rubber allowing sheath to bend without serious damage. Cable is made of braided steel with diameter of 1.5 millimeters. To avoid steel threads disintegrate ending were soldered for strength. Cable drums are designed with helical groove with diameter of 1.7 millimeters to fix cable while translation and provide stable data without sharp shifts. Motors are connected to Escon controller 50/5 which provided precise control. Motor controllers are connected to DAQ which sends data to simulink and vise versa. Angle encoder is connected to DAQ directly as it does not need power supply from external sources. Force sensors are required to use a signal amplifier, as signal from force sensors usually utilize millivolts voltage level. After being processed in amplifier, signal is sent to DAQ to be accounted. Two DAQ were used in experiments due to hardware limitation.

### 3.3 Bowden Cable Actuation System

Cable system is driven by utilizing Bowden cables. Bowden cable consists of inner steel cable and outer sheath. As antagonistic system is researched in thesis therefore two cables were installed. The role of one cable is flexion movement and second is extension movement respectively. Cable sheath and cable itself were described in previous section. Length of cable in all configuration is same, but length of translation vary with configuration geometry. While being bended cable experiences more friction than in straightened pose. Sheath does not contain technical oil, so contact between cable and sheath is always dry.

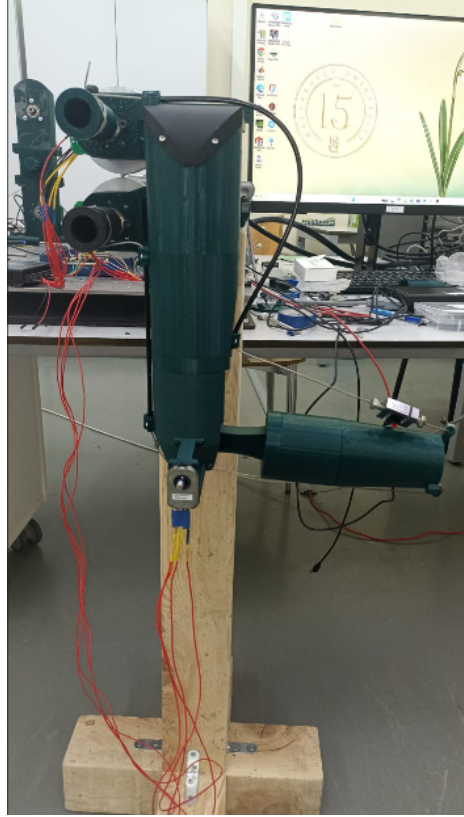


Figure 3-1: Extended elbow

### 3.4 Cable Routing Configurations

Six possible cable configurations were developed during research. All configurations were designed in 2D space. All of them has own cable translation length, cable sheath bending angle and anchoring points. All configurations are presented in picture below.

Each configuration has altering moment arm during movement so simulation model was developed in Matlab to obtain data of moment arm for future experiments.

From modeled prototype motion we obtained data about moment arm related to time and angle

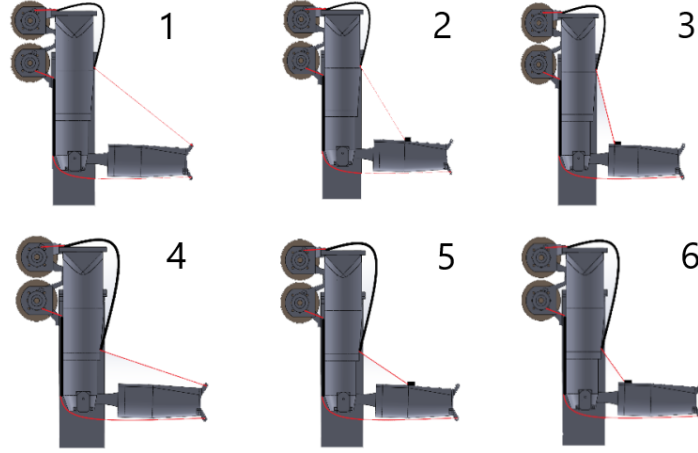


Figure 3-2: Different Bowden cable routing configurations (1–6)

### 3.5 Sensors and Instrumentation

To account for angle change it is decided to use encoder AMT-102V. It is located on elbow joint to track forearm angle change.

To find out how much force was delivered to joint tension sensors MLS66 were installed.

### 3.6 Data Acquisition and Control Hardware

Equipment utilized for control: DAQ PCI 68A (6343), Matlab 2024b/Simulink, Escon 50/5 motor driver.

Current system setup allows obtain and send signals to ESCON motor controller and obtain signals directly from encoder or force sensor signal amplifier. Encoder is directly connected to DAQ as it does not needed to have external power supply. Force sensors utilizes signal amplifiers because signal from force sensor reached only millivolts voltage level. Escon motor are supplied with power from RIGOL DP power supply equipment, but all signals wires are connected to both motor and DAQ. Maxon motor 380619 are equipped with hall sensors so ESCON motor controllers provides

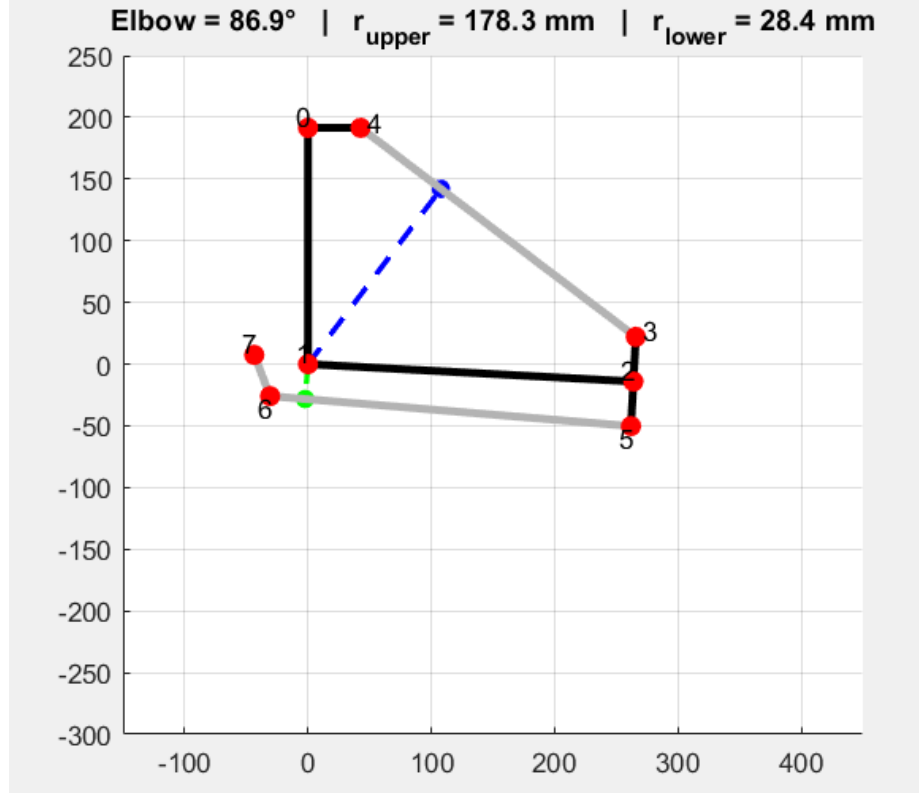


Figure 3-3: Matlab simulation model, where blue line - upper moment arm, green - lower moment arm

accurate current and voltage supply to motor in doing so make speed adjustable.

### 3.7 Theoretical reference model

To validate experimentally estimated joint torque, simplified analytical model based on gravitation was developed. Forearm is modeled as rigid link with mass center approximately at the center of forearm. Dynamic effects were neglected in this model. To pick this forearm up the required torque is estimated as:

$$\tau = mgl \sin(\theta) \quad (3.1)$$

where  $m$  is the forearm mass,  $g$  is gravitational acceleration,  $l$  is the distance to the center of mass, and  $\theta$  is the elbow angle.

The model predicts a peak torque of approximately 1.6 N·m, which is consistent

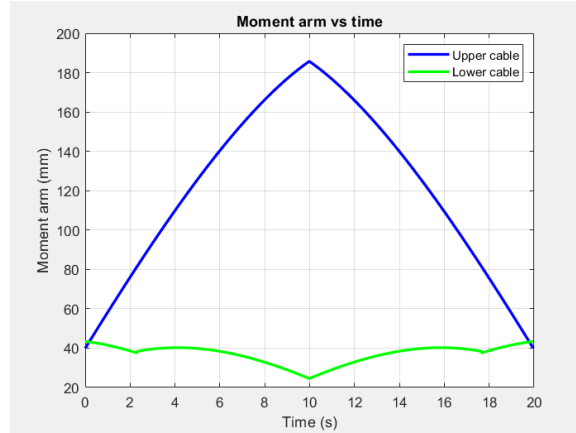


Figure 3-4: Moment arm vs. time

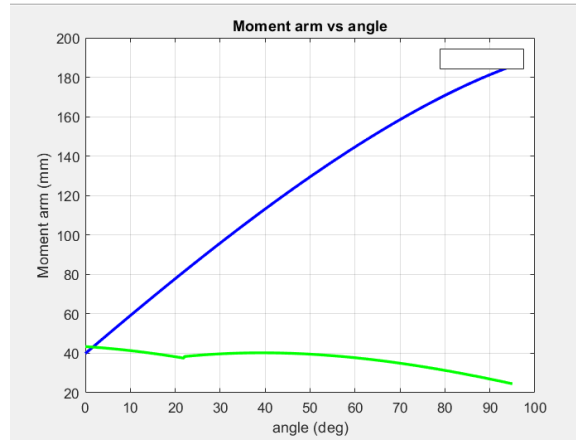


Figure 3-5: Moment arm vs. angle

with the experimentally obtained values. This model supports the physical credibility of the proposed torque estimation method.



Figure 3-6: Angle encoder AMT102-V



Figure 3-7: Tension sensor MLS66

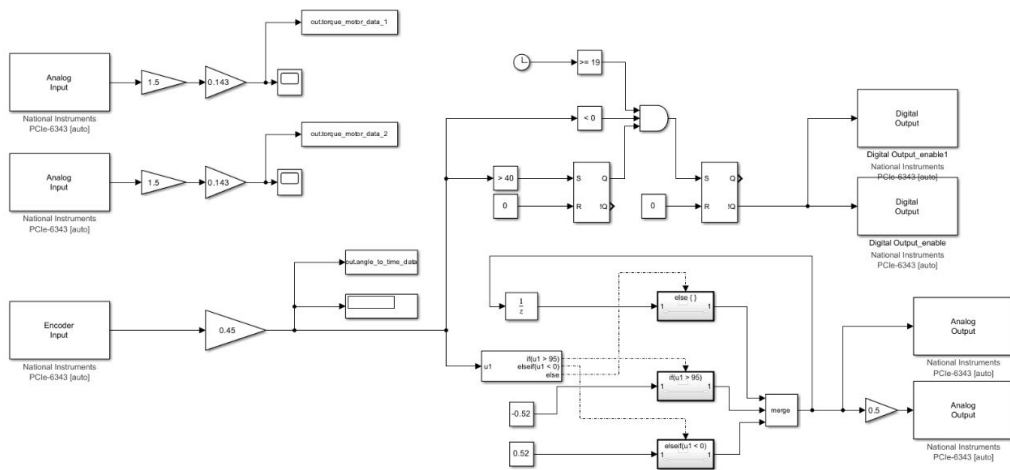


Figure 3-8: Matlab control scheme

# Chapter 4

## Experimental protocol

The objective of experimental protocol is to evaluate how different cable routing configurations affect torque transmission in cable-driven system. The experiments aim to quantify joint torque based on data obtained several types of equipment: force sensors, angle encoder, Maxon motor hall sensors and data received from Matlab simulations. This will allow analyze impact of routing geometry on transmission efficiency. Hysteresis anticipated from experiments.

All experiments were conducted with same conditions for scientific credibility. It is decided to control prototype to flex arm only for 95 degrees in flexion. This range of motion is dictated by each configuration constraint, where 95 degree is a range which is reachable for all routing.

Motor speed is important parameter for torque estimation, but due to geometrical distinctions between routings it is decided to neglect difference. Range of difference 10-15 percent of all speed. It is important to note than speed of flexion motor is always faster than extension motor on two times.

General time of all experiments is 20 seconds as it provides obvious view of trends in graphs which is easier to observe and interpret later. In each configuration 10 seconds were devoted to flexion movement phase and same time for extension one.

Force sensors and angle encoder has errors while operating on prototype. Therefore, to detect true data, experiments were conducted several times until authors can see stably repeating data.

Due to lack of equipment, experiment were conducted separately for upper and lower cable with force sensors.

To control prototype control scheme in Simulink software was developed. It provided consistent and stable control, which is important in terms of our experiments.

Each experimental run experienced same amount of load. Weight of forearm is constant and equals to 984 grams. As filler is placed tightly inside forearm, mass center never changes during movements.

Pretension is neglected, because during experiment it is revealed that it does not affect data sufficiently.

From experiments several measured variables were obtained. They are: Force sensor from upper and lower cables, angle from elbow encoder, time (from simulink software) and current from motor hall sensors. Also data of moment arms were obtained from Matlab simulations.

Motor torque was estimated from measured motor current using an approximate torque constant. Constant was calculated from the motor speed constant, due to the unavailability of original datasheet. General formula for torque constant used:

$$K_t \approx \frac{60}{2\pi \cdot 66.8} \approx 0.143 \text{ Nm/A} \quad (4.1)$$

Data processing was also required to be carried out as each signal has noise. Data processing was used on current data from motor hall sensors. During experiments data from force sensors was filtered by low-pass filter for future convenience.

Data synchronization is carried out based on time values, where 10 seconds serve as indicator of motor direction switching.

# Chapter 5

## Experimental Results and Torque Loss Characterization

From conducted experiments it is revealed that each configuration has particular range of motion. This happens due to anchoring point location of forearm.

| Configuration number | Angle with force sensor | Angle without force sensor |
|----------------------|-------------------------|----------------------------|
| 1                    | 133°                    | 133°                       |
| 2                    | 132°                    | 133°                       |
| 3                    | 113°                    | 126°                       |
| 4                    | 108°                    | 113°                       |
| 5                    | 120°                    | 117°                       |
| 6                    | 95°                     | 125°                       |

Table 5.1: Comparison of angles with and without force sensor

Several types of data were received from experiment. Here is current data which was received from hall current sensors which is instantly converted to motor torque. As signal had a noise filter was applied.

Force sensors data after low-pass filtering.

After filtering all motor torque were summarized in the picture below.

Same was done for motor 2

Obtained data from both motors were used to calculate net motor torque:

$$\tau_{\text{motor, net}} = \tau_{\text{flex}} - \tau_{\text{ext}} \quad (5.1)$$

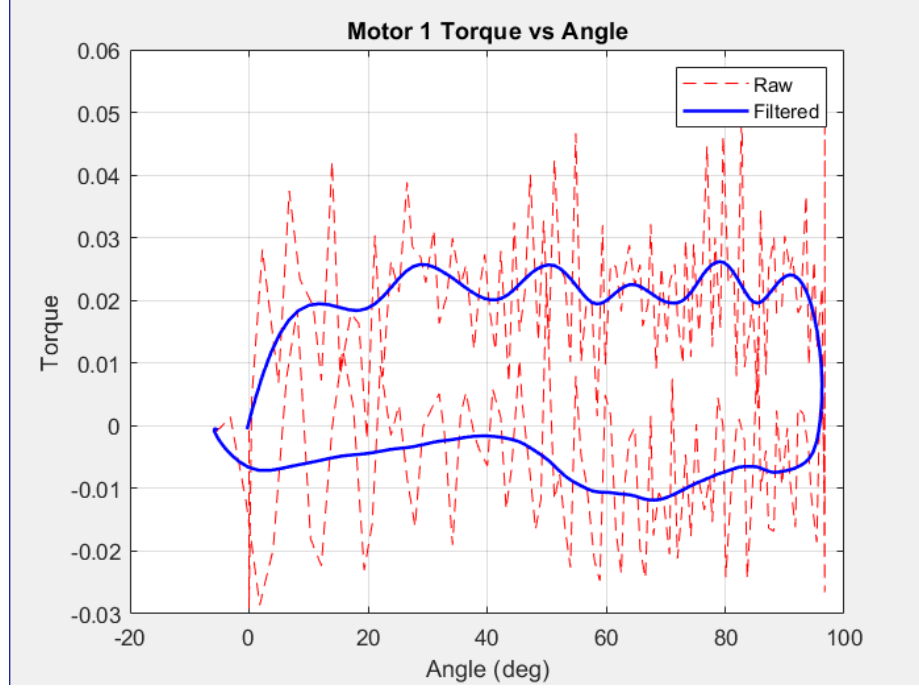


Figure 5-1: Raw and smoothed torque

After graphs were obtained hysteresis loop area was computed. Results are illustrated in the table:

| Configuration | Motor 1 | Motor 2 | Net    |
|---------------|---------|---------|--------|
| 1             | 0.0430  | 0.0421  | 0.0193 |
| 2             | 0.0473  | 0.0419  | 0.0097 |
| 3             | 0.0547  | 0.0379  | 0.0168 |
| 4             | 0.0531  | 0.0431  | 0.0103 |
| 5             | 0.0498  | 0.0352  | 0.0151 |
| 6             | 0.0618  | 0.0390  | 0.0227 |

Table 5.2: Motor torques for different configurations

Using moment arm data obtained from Matlab simulations and data from force sensors be calculated joint torque and compared it with each other.

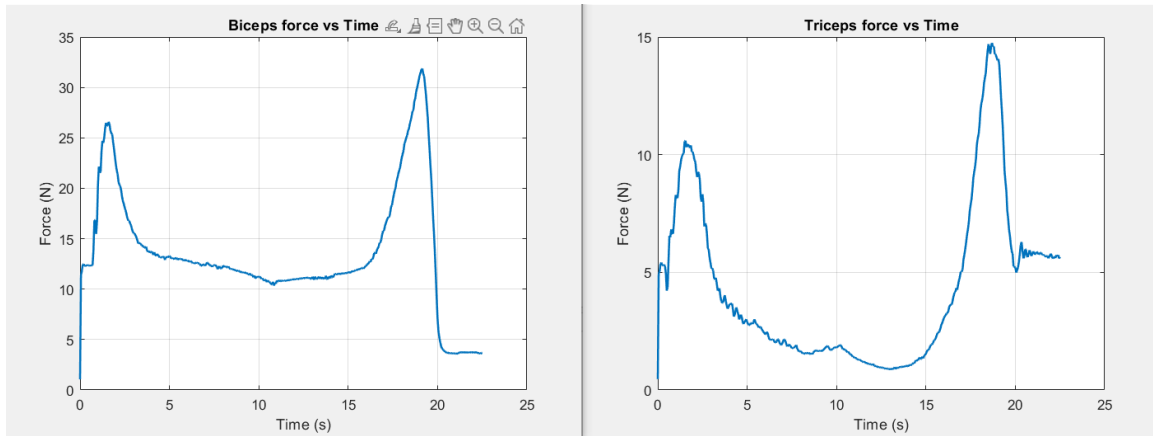


Figure 5-2: Force vs time (biceps and triceps)

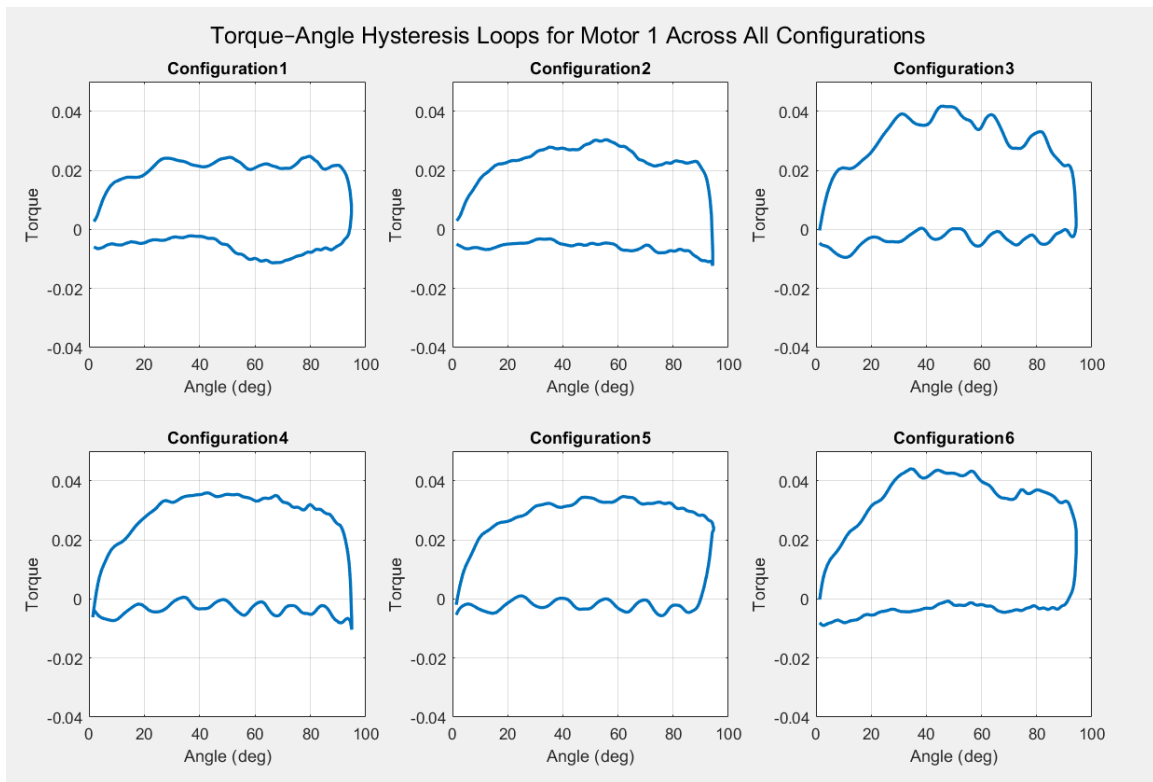


Figure 5-3: Motor 1 torque vs angle comparison

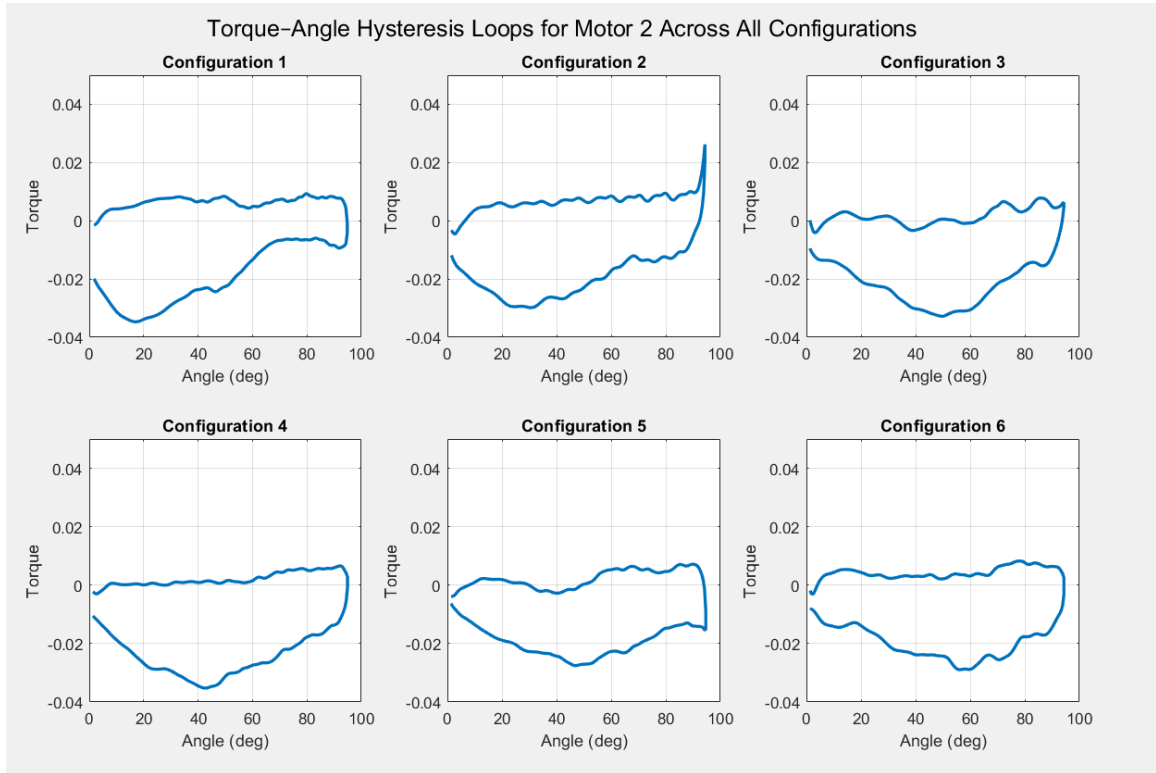


Figure 5-4: Motor 2 torque vs angle comparison

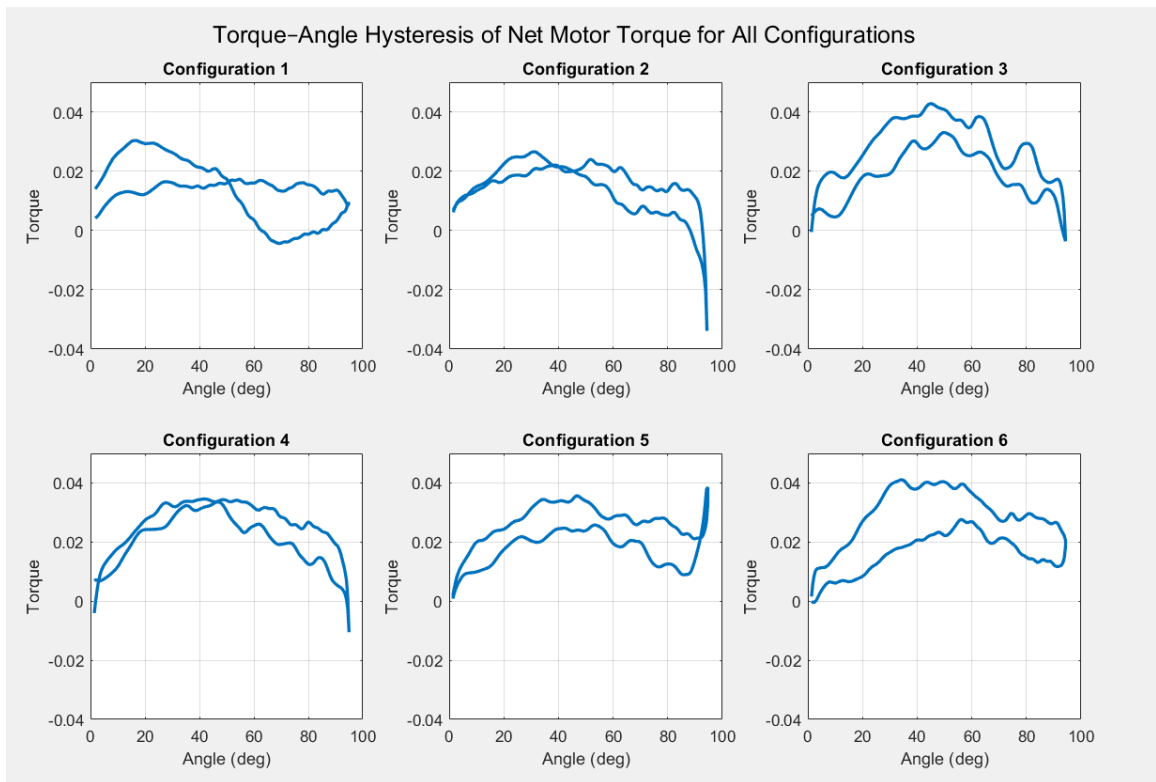


Figure 5-5: Net motor torque comparison

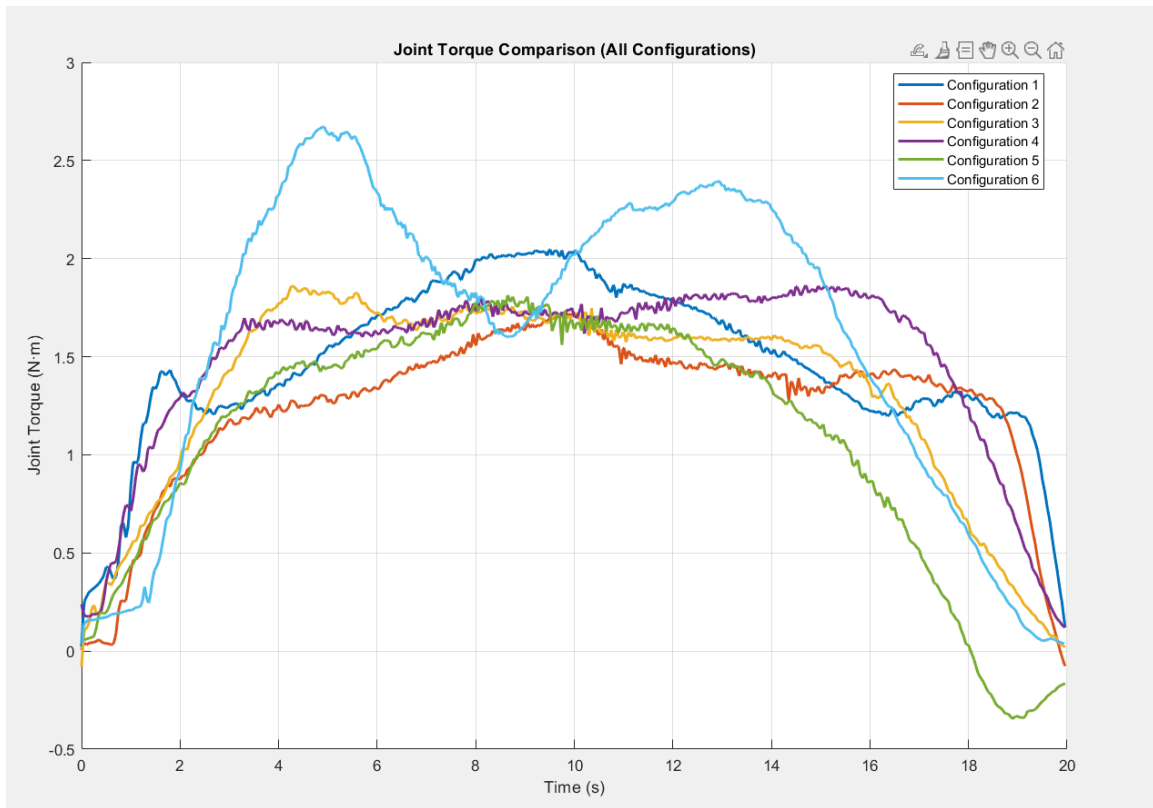


Figure 5-6: General joint torque comparison

# Chapter 6

## Discussion

Obtained data provide important information about configuration differences. Despite same experimental conditions like trajectory and time, different configurations illustrates variability in final results.

First noticeable details are peak values. It can be obviously observed across configurations. For instance configuration 6 reaches peak at 2.6-2.7 Nm. Perhaps, this happens due to close anchoring point placement, where force sensor pulled forearm near to joint and far from mass center.

On the other point of view, theoretical Matlab simulation revealed that all configuration reaches peak at 1.6 Nm. This fact is proved by figure 5.6, where all variations converges nearly 1.6 at peak.

Secondly, shapes of curves are not same. Some configurations show smoother and more stable (configurations 1 and 6), while other exhibits fluctuations or sharp drops. This fact can be evidence that cable routing can introduce nonlinear behavior to system like micro-slips.

Thirdly, configurations obviously shows that with some anchoring point location it is required less force to raise forearm than other. As it is seen from graph, configuration 5, where forearm anchoring point is located directly on mass center require less force to raise.

Another important observation is divergence after 15 seconds. We can see that lines decreases different way despite they intersect at ending stage. Some of them fall

dramatically, while other gradually lowers. This behavior can be attributed to slack, changes in contact. Such pose-dependent losses confirm that torque transmission is not constant.

Hysteresis loop of motor illustrates system behavior from another point of view - from force generation side.

Calculated hysteresis loop areas provide quantitative measure of energy losses in each configuration. Larger loop corresponds to greater energy dissipation while small loop area - to insufficient energy losses.

From the table, configuration 6 exhibits the highest net hysteresis area (0.0227). In contrast, Configuration 2 shows the lowest value (0.0097) suggesting more efficient torque transmission. This happens due to height of anchoring point on the biceps side and location of attachment point on forearm directly on mass center. This observation suggest that attachment point on mass center with short cable sheath give optimized solution to low torque loss.

Noticeable distinction is that individual motor hysteresis is not always equal to same net hysteresis. For example, configuration 3 has the highest Motor 1 value (0.0547), but its net value (0.0168) is lower than configuration 6. This may be evidence to fact that in antagonistic system both cable plays crucial role in interacting.

Another observed fact, imbalance between motor 1 and motor 2 across configurations. It indicated asymmetric system behavior. For instance, in configuration 6 Motor 1 losses (0.0618) are higher than Motor 2 (0.0390), which explains the large net hysteresis. Assumption is that differences can be caused by routing geometry, such as curvature or attachment points location.

From all configurations it is obviously that configuration 2 is most optimized. This fact proves that short length of sheath and cable fixed on center mass is best combination for lowest torque loss and better transmission energy.

Overall, these results support the hypothesis that cable configuration plays a critical role in determining actual joint torque and torque losses.

# Chapter 7

## Future directions

The conducted study researched only 1-DOF elbow joint. Future work should extend analysis to multi-joint systems, where routing becomes more complicated and will play crucial role in energy transmission.

Future studies can develop real-time altering routings systems. In dependence on motion. Various routings may appear more preferable in transmission energy. Self-adjustable systems can most optimized in real time.

Control implications. Understanding of cable system behaviour can be integrated into real-time stimulation algorithms. This control implication can make rehabilitation robotic system much safer.

In addition, human should be included in future research as prototype is stable and quite predictable while human introduces unpredictability but real example of system application.

# Bibliography

- [1] Hassan Qassim and W. Wan Hasan. A review on upper limb rehabilitation robots. *Applied Sciences*, 10:1–18, 10 2020.
- [2] Adriana Daniela Banyai and Cornel Brişan. Robotics in physical rehabilitation: Systematic review. *Healthcare*, 12(17), 2024.
- [3] Xu Liang, Yuchen Yan, Weiqun Wang, Tingting Su, Guangping He, Guotao Li, and Zeng-Guang Hou. Adaptive human–robot interaction torque estimation with high accuracy and strong tracking ability for a lower limb rehabilitation robot. *IEEE/ASME Transactions on Mechatronics*, 29(6):4814–4825, 2024.
- [4] Ming Xu, Zhihao Zhou, Zezheng Wang, Lecheng Ruan, Jingeng Mai, and Qining Wang. Bioinspired cable-driven actuation system for wearable robotic devices: Design, control, and characterization. *IEEE Transactions on Robotics*, 40:520–539, 2024.
- [5] Urs A. T. Hofmann, Tobias Bützer, Olivier Lambercy, and Roger Gassert. Design and evaluation of a bowden-cable-based remote actuation system for wearable robotics. *IEEE Robotics and Automation Letters*, 3(3):2101–2108, 2018.
- [6] Mingrui Luo, En Li, Zhangxi Zhou, George Mylonas, Gang Chen, and M. Tan. Reducing and compensating hysteresis in bowden cable-driven manipulators via optimized transmission paths and improved tension modeling. *IEEE/ASME Transactions on Mechatronics*, PP:1–13, 12 2025.
- [7] Hankyung Im, Yongchan Kim, and Sangrok Jin. Hysteresis modeling and compensation in antagonistic tendon-sheath mechanisms via tension detection under various conditions. *IEEE Access*, 13:189528–189541, 2025.
- [8] Yaodong Lu, Yannick Aoustin, Pablo Nocito, Sébastien Mick, and Nathanaël Jarrassé. Design and experimental validation of a controller for bowden-cable actuators subject to friction variation. *IEEE Robotics and Automation Letters*, 10(9):9264–9271, 2025.
- [9] Zhiquan Chen, Jiyuan Wu, Chunqi Ju, Xingsong Wang, Mengqian Tian, and Bin Liu. Design and control of a cable-driven exoskeleton system for upper-extremity rehabilitation. *IEEE Access*, 12:187964–187975, 2024.

- [10] Emanuele Bianchi, Elena Bardi, Francesco Braghin, Emilia Ambrosini, Loris Roveda, and Marta Gandolla. A friction compensation strategy for an upper limb exosuit\*. In *2024 IEEE 7th International Conference on Soft Robotics (RoboSoft)*, pages 858–863, 2024.
- [11] Ryo Takei, Samuel Frishman, and John P. Whitney. Design and evaluation of high-performance motion-decoupled cable transmission modules. In *2025 IEEE International Conference on Robotics and Automation (ICRA)*, pages 5089–5095, 2025.
- [12] S. A. F. Taylor, A. E. Kedgley, A. Humphries, and A. F. Shaheen. Simulated activities of daily living do not replicate functional upper limb movement or reduce movement variability. *Journal of Biomechanics*, 76:119–128, 2018.
- [13] Anne Schwarz, Miguel M. C. Bhagubai, Saskia H. G. Nies, Jeremia P. O. Held, Peter H. Veltink, Jaap H. Buurke, and Andreas R. Luft. Characterization of stroke-related upper limb motor impairments across various upper limb activities by use of kinematic core set measures. *Journal of NeuroEngineering and Rehabilitation*, 19(1):2, 2022.
- [14] Saba Anwer, Asim Waris, Syed Omer Gilani, Javaid Iqbal, Nusratnaaz Shaikh, Amit N Pujari, and Imran Khan Niazi. Rehabilitation of upper limb motor impairment in stroke: A narrative review on the prevalence, risk factors, and economic statistics of stroke and state of the art therapies. *Healthcare (Basel)*, 10(2):190, January 2022.
- [15] E Urendes, C Sanchez, S Lerma-Lara, A Rojo, V Costa, and R Raya. Design, development, and functional validation of a 3d-printed passive upper limb exoskeleton. *IEEE Trans. Neural Syst. Rehabil. Eng.*, 32:2503–2512, July 2024.
- [16] Sandesh Bhat, Emily Miller, Paul Kane, Kevin Hollander, Claudio Vignola, Alexander Shin, Thomas Sugar, and Kenton Kaufman. Enhanced functionality using a powered upper extremity exoskeleton in patients with brachial plexus injuries. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, PP:1–1, 02 2025.
- [17] Julia Peladeau, Philippe Garrec, Sébastien Laporte, and Xavier Bonnet. Impact of able 7-axes exoskeleton on upper limb kinematics during movements. *Journal of Biomechanics*, 192:112953, 2025.
- [18] Longbao Chen, Ding Zhou, and Yuquan Leng. A systematic review on rigid exoskeleton robot design for wearing comfort: Joint self-alignment, attachment interface, and structure customization. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 32:3815–3827, 2024.
- [19] Yexun Wei, Dezhi Yang, Miao Feng, Jianing Sun, and Guoying Gu. A fabric-based soft elbow exosuit with autonomous anchoring straps. In *2025 IEEE 8th International Conference on Soft Robotics (RoboSoft)*, pages 1–6, 2025.

- [20] Juwairiya Siraj Khan, Mostafa Mohammadi, John Rasmussen, Shaoping Bai, and N.S. Lotte Andreasen Struijk. A review on the design of assistive cable-driven upper-limb exoskeletons and their experimental evaluation. In *2022 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 59–64, 2022.
- [21] Pengcheng Li, Shuxiang Guo, Jun Leng, and Weiyu Chen. Cure: A cable-driven upper-limb rehabilitation exoskeleton for assisting adls in home-based environment. In *2025 IEEE International Conference on Mechatronics and Automation (ICMA)*, pages 764–769, 2025.
- [22] Ruqi Ma, Zixin Tang, Xiangyu Gao, and Wencheng Ni. Mechanism design and kinematics analysis of an original cable-driving exoskeleton robot. In *2018 2nd IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*, pages 1869–1874, 2018.
- [23] Wei Wei, Zhicheng Qu, Wei Wang, Pengcheng Zhang, and Fuchun Hao. Design on the bowden cable-driven upper limb soft exoskeleton. *Appl. Bionics Biomech.*, 2018:1925694, July 2018.
- [24] Sungjae Min, Hyungjoo Kim, and David Shim. Antagonistic bowden-cable actuation of a lightweight robotic hand: Toward dexterous manipulation for payload constrained humanoids, 12 2025.
- [25] Youngmok Yun, Priyanshu Agarwal, Jonas Fox, Kaci E. Madden, and Ashish D. Deshpande. Accurate torque control of finger joints with ut hand exoskeleton through bowden cable sea. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 390–397, 2016.
- [26] Useok Jeong and Kyu-Jin Cho. Control of a bowden-cable actuation system with embedded boasensor for soft wearable robots. *IEEE Transactions on Industrial Electronics*, 67(9):7669–7680, 2020.
- [27] Miha Dežman, Tamim Asfour, Aleš Ude, and Andrej Gams. Mechanical design and friction modelling of a cable-driven upper-limb exoskeleton. *Mechanism and Machine Theory*, 171:104746, 2022.
- [28] Andrew Borowski, Alexander Metz, and Fabrizio Sergi. Dynamic model of cable-conduit actuation for interaction with non-passive environments. In *2018 IEEE Haptics Symposium (HAPTICS)*, pages 40–45, 2018.
- [29] Useok Jeong and Kyu-Jin Cho. A feasibility study on tension control of bowden-cable based on a dual-wire scheme. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*, pages 3690–3695, 2017.
- [30] Useok Jeong and Kyu-Jin Cho. Feedforward friction compensation of bowden-cable transmission via loop routing. 10 2015.

- [31] Daniel Pérez-Suay, Yu Li, Hamid Sadeghian, Djallil Naceri, and Sami Haddadin. Torque transmission in double-tendon sheath driven actuators for application in exoskeletons. pages 4751–4757, 05 2024.
- [32] Yansong Wang, Ahmad Zahedi, Yanzheng Zhao, and Dingguo Zhang. Extracting human-exoskeleton interaction torque for cable-driven upper-limb exoskeleton equipped with torque sensors. *IEEE/ASME Transactions on Mechatronics*, 27:4269–4280, 12 2022.
- [33] Matthias Jammot, Adrian Esser, Peter Wolf, Robert Riener, and Chiara Basla. A comparative study of pulley and bowden transmissions in a novel cable-driven exosuit, the stillsuit. pages 2494–2500, 05 2025.
- [34] Yang Liu and Farshid Alambeigi. Effect of external and internal loads on tension loss of tendon-driven continuum manipulators. *IEEE Robotics and Automation Letters*, 6(2):1606–1613, 2021.
- [35] Dongyang Chen, Youngmok Yun, and Ashish D. Deshpande. Experimental characterization of bowden cable friction. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, pages 5927–5933, 2014.
- [36] Xin Chen, Guanbin Gao, Jing Na, Yashan Xing, Haoran He, Mengmeng Yan, and Sheng Lu. Modeling and identification of double-cable-driven exoskeleton with asymmetric dynamic friction. *IEEE/ASME Transactions on Mechatronics*, 30(6):7298–7307, 2025.