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A Novel Powered Jaw Exoskeleton to Treat Temporomandibular Disorders: Design and Control Challenges

Paul-Otto Müller[1] and Oskar von Stryk[1]

***Abstract*— Temporomandibular disorders severely impair masticatory function and quality of life. While powered jaw exoskeletons offer potential for rehabilitation, they are not well researched and face challenges related to complex biomechanics and safe force transmission. This paper presents a novel hybrid active jaw exoskeleton design that addresses these issues by combining a rigid chin mechanism for precise force application with a compliant facial interface for enhanced safety. We develop a high-fidelity *MuJoCo* simulation and outline a control concept to handle partial observability and soft dynamics. This integrates a learned, deformation-aware dynamics model with latent states into a constrained, differentiable model predictive control scheme tuned via RL. This work establishes a foundation for future safe, wearable robot-assisted therapy for temporomandibular disorders.**

I. INTRODUCTION

The human masticatory system is one of the most intricate musculoskeletal systems in the body. It features two joints connecting the mandibular condyles to the temporal bone, supported by viscoelastic discs that enable complex six-degree-of-freedom motion while absorbing substantial shear and compressive loads [1]. Temporomandibular disorders (TMDs) constitute a major healthcare burden, affecting approximately 5–12% of the global population as a diverse group of musculoskeletal and neuromuscular conditions [2]. These disorders manifest as pain, restricted mobility, and stiffness, severely impairing essential daily functions such as chewing, speaking, and swallowing [3]–[5]. Active jaw exoskeletons may offer a promising approach for TMD rehabilitation by delivering controlled assistive or resistive forces during therapy and objectively tracking biomechanical metrics. However, the development of such devices is yet not well researched and hindered by significant challenges: the complex biomechanics of the jaw, the strict requirement for safe power transmission near sensitive facial structures, and the need for adaptive control strategies that accommodate varying patient impairments and anatomies [3], [6]. Progress in this field remains limited, largely due to its novelty and the scarcity of high-fidelity simulation frameworks useful for rapid prototyping and evaluation. To the best of our knowledge, only five active jaw exoskeletons have been reported in the literature to date [7]–[11], each with distinct design philosophies and limitations, e.g., no comprehensive model framework, rigid structures, or limited motion capabilities [3]. To address the critical trade-off between effective force transmission and user safety, we propose a hybrid exoskeleton architecture [12], [13]. This paradigm moves beyond purely rigid or purely soft designs by combining rigid mechanisms for structural integrity with soft, compliant interfaces and materials for facial contact. This hybrid approach ensures robust force delivery to the mandible while distributing contact pressure to enhance user comfort and safety. We employ tendon-driven actuation to leverage its inherent compliance and lightweight profile. While advantageous, implementing robust control for tendon-driven systems is challenging due to unilateral actuation, possible redundancy, and soft, deformable interfaces and structures. Furthermore, ensuring precise mandibular tracking without excessive pressure on soft facial tissues and power-transmission interfaces remains a significant challenge. In this work, we present the design and modeling of a novel, tendon-driven hybrid jaw exoskeleton. We detail the development of a comprehensive simulation model and discuss the specific control challenges and planned solutions for enabling the safe and adaptive rehabilitation of TMDs using wearable robotics.

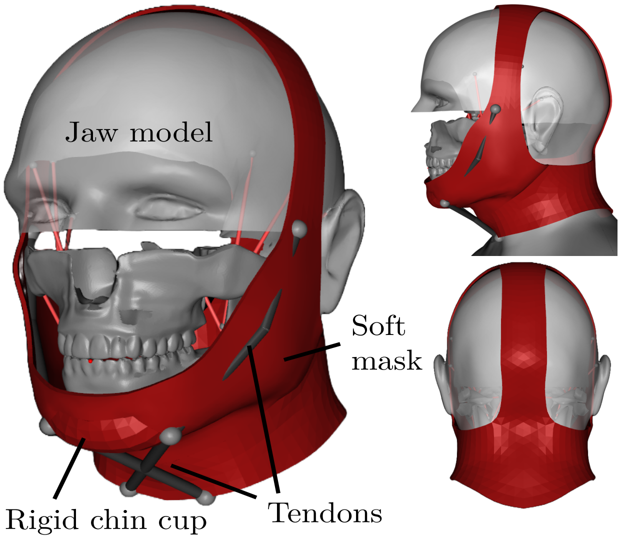

Fig. 1: Hybrid rigid-soft jaw exoskeleton model in *MuJoCo*, featuring a biomechanical jaw model, a rigid chin cup for force transmission, and a soft facial mask for safe user interaction. The four tendon-driven actuators provide controlled assistance and resistance during therapeutic exercises.

II. SYSTEM DESIGN AND SIMULATION

The design of the novel powered jaw exoskeleton centers on a hybrid rigid-soft structure that combines a rigid chin cup for effective force transmission with a soft facial mask to ensure user comfort and safety during operation, leveraging

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[1] Simulation, Systems Optimization and Robotics Group, Technical University of Darmstadt, Darmstadt, Germany `{pmueller, stryk}@sim.tu-darmstadt.de`

the inherent compliance of soft materials to distribute contact forces and minimize pressure on sensitive facial tissues. The exoskeleton employs a four-tendon-driven actuation system, connected to the chin cup and routed over the soft mask and head, providing controlled assistance and resistance during therapeutic exercises (Fig. 1). The exoskeleton and masticatory system are designed and modeled in *Blender* and simulated using the *MuJoCo* physics engine, which offers advanced capabilities for simulating complex (soft) multi-body dynamics, contact interactions, and tendon-driven actuation systems [14]. The jaw model incorporates 24 muscles and 4 ligaments, represented as force-generating elements with anatomically accurate attachment points and force-length-velocity relationships, allowing for realistic simulation of jaw kinematics and dynamics across 5 degrees of freedom (DOF). The jaw meshes and model parameters are adapted from the literature [15]. The chin cup is rigidly connected to the mandible, neglecting coupling dynamics. The soft facial mask, which comes into contact with a rigid skin collision mesh, is modeled using a *Saint Venant-Kirchhoff* hyperelastic material model implemented via piecewise linear finite elements to accurately capture deformation behavior under contact and loading conditions. The initial material properties are chosen based on 3D-printable TPU (Young's modulus: $17.4\,\mathrm{MPa}$, Poisson's ratio: 0.46) [16], [17]. Each cable actuator is modeled using *MuJoCo*'s general actuator with a $75\,\mathrm{N}$ maximum force, matching requirements for opening forces [3], first-order activation dynamics ($30\,\mathrm{ms}$ time constant), and series compliance ($10\,\mathrm{N/mm}$ stiffness, $10\,\mathrm{Ns/m}$ damping). These properties could represent, for instance, a combined Bowden cable, *Maxon EC 45 flat* motor, and $15:1$ gearbox system. The model is validated using experimental jaw trajectories from a healthy subject performing various jaw movements and is evaluated in simulation for kinematic tracking accuracy, contact forces, and stresses and strains at the soft facial interface [12], [13], [18].

III. CONTROL CHALLENGES AND STRATEGIES

Controlling such a complex, coupled human-exoskeleton system poses several challenges in simulation and in reality. Contact-rich and discontinuous dynamics can arise from cable taut/slack transitions and intermittent face–mask contact, leading to non-smooth forces that can destabilize model-based control rollouts. Parameter identifiability issues also arise, as multiple parameter sets (cable stiffness, damping, friction, and contact softness) can explain similar trajectories, rendering learned dynamics ill-posed without priors or regularization. Although the four-tendon configuration is redundant for the 3 DOF Cartesian positioning task, the unilateral constraint requires explicit tension allocation. While the redundancy admits a manifold of valid tension solutions for a given force, naïve inversions (e.g., unconstrained least-squares) frequently violate physical limits by requesting negative tensions (pushing). Partial observability of human states poses challenges when the control policy only observes jaw pose and velocity, but not mask deformation or contact state, making the dynamics history-dependent. For instance, learned one-step models may fail over a model predictive control (MPC) horizon. Finally, long-horizon error compounding occurs, in which small model errors in contact or tendon stiffness can explode over short horizons. In a real system, additional challenges include unmeasured human states, such as true jaw muscle activation, soft-tissue compliance, and jaw joint friction, which are hidden and time-varying due to factors like fatigue and pain guarding. Safety-critical constraints must be enforced, including hard limits on tendon tension, jaw torque, and contact pressure. Calibration drift and donning variability also affect performance, as mask fit changes between sessions and cable routing and pretension vary, altering moment arms and effective stiffness. Delays and bandwidth limits from motor drivers, sensing, and filtering introduce latency, requiring a feasible control bandwidth that spans slow therapeutic cycles without exciting soft-interface dynamics.

To tackle part of these challenges, we plan to test a control pipeline that couples learned, deformation- and contact-aware dynamics with constrained MPC and safety-preserving RL-based tuning in the future. While the *MuJoCo* simulation offers full state transparency, critical interface states, such as mask deformation, are difficult to measure or estimate in reality. To address this, we plan to learn a dynamics model $\boldsymbol{x}_{t+1} = f_\theta(\boldsymbol{x}_t, \boldsymbol{z}_t, \boldsymbol{u}_t)$ (using simulation and real data) that augments the observable state with a low-dimensional latent vector $\boldsymbol{z}_t$. This latent vector is automatically learned to capture unmeasured compliance and contact dynamics, effectively providing the model with additional internal degrees of freedom to represent these unobservable relationships. At runtime, z_t is inferred from the history of available sensors (e.g., IMU kinematics, tendon force, mask pressure, and EMG) via a recurrent encoder, ensuring the predictive model becomes approximately Markovian despite partial observability. The resulting model is then used in an MPC that explicitly enforces safety constraints (tendon tension bounds, jaw velocity/acceleration bounds, pressure limits, and other safety and comfort metrics), while handling redundant, unilateral tendons directly within the MPC optimization by treating tendon forces as control inputs. This approach inherently enforces constraints ($F \geq 0$, maximum tension) and minimizes effort and asymmetry over the prediction horizon. To address the accumulation of prediction errors over long horizons and the objective mismatch inherent in sequential system identification and manual controller tuning, the MPC is made differentiable and treated as a policy class, enabling end-to-end adjustment of cost weights (tracking vs. effort vs. comfort proxies) and selected dynamics parameters directly from closed-loop performance gradients, as in differentiable MPC formulations [19], [20]. Consequently, Reinforcement Learning (RL) is employed to drive this optimization process. Instead of learning a black-box control policy, RL updates the parameters of the MPC (such as cost weights and constraint margins), effectively using the MPC as a safety filter that guarantees constraint satisfaction while the high-level strategy adapts to maximize task performance [19]. We plan to build a prototype using 3D printing techniques.

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