My Ph.D. project entitled "Optimization of pianists' whole-body gestures through the integration of experimental and simulation research approaches" aims to explore innovative kinematic strategies that might help pianists optimize performance and reduce the risks of injury.

To do this, I will focus on three keywords: **Injury prevention** (Playing related musculoskeletal disorders), **Optimal Control theory**, and **Proximal Movements**.

Here also is the question I would like to address:

How can biomechanical analysis and predictive simulations based on optimal control theory be utilized to identify pianists at high risk for musculoskeletal disorders, and what are the implications for developing preventative strategies?

To enhance reading efficiency and facilitate understanding, I have italicized technical terms.

Introduction

The delicate balance between the piano playing art and the pianists' physical health is a long-standing area of interest within both musical and medical communities [1]. The challenge is to keep pianists healthy without compromising their art. *Playing-related musculoskeletal disorders* (PRMDs) are a critical concern, as they might impact a pianist's ability to perform, often leading to injuries, reduced functionalities, and even the need to cease professional activities [2, 3, and 4]. *Optimal control theory*, a mathematical-based framework, guides us in finding the best possible ways to perform tasks or make decisions within *certain constraints (bounded conditions or parameters)* [5, 6]. It's particularly useful for understanding how pianists can avoid musculoskeletal disorders. This theoretical framework allows us to construct and analyze *comprehensive predictive models* [7, 8] that simulate various piano-playing strategies. By simulating different scenarios and control strategies, researchers can identify the most effective ways to optimize performance and reduce injury risks, providing valuable insights for developing pedagogical and preventative strategies. The literature emphasizes the complexity of PRMDs among musicians, attributing their occurrence to various factors ranging from individual anatomy to practice habits and ergonomic considerations at the instrument [9]. In the following sections, I will explore the background of the most important biomechanical studies in piano performance, describe the existing methodology for analyzing biomechanical profiles and developing a predictive model, and discuss the implications for piano pedagogy and performance health.

Literature

Zaza et al. (1998) first used the term "playing-related musculoskeletal disorders" to describe musculoskeletal symptoms that interfere with the ability to play an instrument: "any pain, weakness, numbness, tingling, or other symptoms that interfere with your ability to play your instrument at the level you are accustomed to" [10]. The kind of instrument, extended practice sessions with little time for rest, poor postural condition, and overusing and fatigued muscles are some of the most commonly mentioned characteristics linked to the development of PRMDs in musicians [11, 12–14].

Research conducted by Gilles Comeau et al. [15] employs infrared imaging to study injuries in pianists. This method detects temperature changes in the hands and arms, areas often affected by musculoskeletal disorders. Such temperature variations signal stress or inflammation, key indicators of potential injury. It identifies temperature differences in pianists experiencing pain, suggesting inflammation, while no significant differences were noted in the lower or upper arms. This approach is significant for its non-invasive nature and potential in early injury detection. However, limitations include a small participant pool and reliance on subjective pain reports, which could introduce bias, highlighting the need for broader studies to confirm these findings and explore infrared imaging's full potential in injury prevention.

Another study examines *proximal* (*closer to the body's center) to distal (farther from the body's center)* [PDS] expert pianists during *pressed-staccato keystrokes*, investigating whether trunk motion helps in upper-limb movement sequencing. It found evidence of PDS across the kinematic chain, with trunk motion enhancing anticipatory shoulder movements, suggesting trunk involvement might optimize performance and reduce injury risks. However, the study's focus on isolated keystrokes and a small participant pool may limit generalizability to broader piano performance contexts, indicating a need for further research on PDS in more complex musical passages and larger samples [16].

The existing literature highlights the risk of musculoskeletal disorders in pianists, mostly due to repetitive movements and prolonged static postures [17, 18-20]. However, much of this research relies on individual case studies or subjective methods, pointing to a significant gap in generalized analysis. Adopting a biomechanical approach to study these concerns can offer a more systematic and scientific lens, potentially overcoming limitations of subjectivity by providing quantitative data on how pianists' movements contribute to injury risks. This approach helps create targeted plans to prevent injuries in pianists by looking at each musician's specific biomechanics. It involves creating a *3D biomechanical model* focused on the upper body to simulate how pianists use *struck and pressed touches during loud notes*. This differentiation is pivotal because struck and pressed touches engage muscles and joints differently, affecting the biomechanical load and potential injury risk. In the struck touch, the fingertip arrives at the key surface with a certain speed, accelerating the key in a sudden, percussive manner. With pressed touch, a fingertip already resting at the key surface and pressing it down by accelerating it gradually [21]. These touches can be analyzed under contrasting conditions: one with an actively engaging trunk (*dynamic trunk (DT)* strategy) and another with a stationary trunk (*static trunk (ST) strategy*). This comparison aims to understand their respective biomechanical implications, with a specific focus on *minimizing torque* at the distal joints to reduce the risk of PRMDs. The DT hypothesized that involving the trunk's larger muscle groups in piano keystrokes redistributes biomechanical loads, reducing torque on the vulnerable distal joints. In contrast, the ST strategy posits a shift of greater biomechanical load to the shoulder joints, increasing distal joint torque due to absent trunk compensatory movements. The approach of weighted torque minimization in biomechanical modeling, especially with an enhanced focus on the metacarpophalangeal (MCP) joint and wrist, addresses their high vulnerability to overuse injuries in pianists. Adjusting the model to prioritize these critical joints makes the simulation more precise in identifying and mitigating injury risks. The distinction between DT and ST strategies allows for an in-depth analysis of how various playing techniques impact pianists' biomechanical health.

Metrics for Biomechanical Analysis

There are three primary analytical tools to evaluate the biomechanical impact of trunk movement strategies on piano playing: the *Area Under the Curve (AUC)* of the *squared torque* for the distal package, the *mechanical work* done by joints [22], and the *dimensionless jerk metric* [23]. These tools enabled a comprehensive assessment of the DT and ST strategies, with a focus on their implications for the development of PRMDs.

The study by Stefanyshyn et al. (2006) supports the significance of the torque-time graph's AUC, or *impulse*, in biomechanics, highlighting its role in predicting injuries in runners due to knee angular impulse. Similarly, understanding the impulse on distal joints such as fingers and wrists is essential in piano playing. High impulse indicates increased demand and potential for *overuse injuries*. This analogy underscores the utility of biomechanical insights in developing strategies to minimize injury risks across activities [24].

The *"Mechanical Work"* metric measures how much energy is used in joint movements when playing the piano. It shows which playing techniques might cause the most strain or be less efficient. This concept relates to the energy flow from proximal to distal parts, suggesting that optimizing this flow can enhance movement efficiency and reduce the likelihood of injury by ensuring energy is used effectively, preventing unnecessary strain on specific joints.

The study "Smoothness Metrics in Complex Movement Tasks" by Gulde and Hermsdorfer [25] explores different methods for *quantifying movement smoothness* in daily activities, focusing on the elderly versus young participants performing a tea-making task. Four parameters were assessed: the number of velocity peaks per meter, spectral arc length, speed metric, and log *dimensionless jerk.* The log dimensionless jerk was found most appropriate for analyzing activities. Therefore, the application of the *Dimensionless Jerk Metric* to piano playing provides a solid framework for analyzing and enhancing performance techniques. By promoting smoothness in motion, this metric directly contributes to *reducing mechanical load on pianists*, significantly reducing the risk of injury.

In conclusion, optimal control theory and biomechanical models are instrumental in simulating and analyzing various piano-playing scenarios, taking into account consistent sound intensity and keystroke duration among other parameters. This advanced approach enables a detailed examination of how different playing techniques, like struck and pressed touches, distribute biomechanical load across both distal and proximal joints. By doing so, it offers a comprehensive understanding of potential injury mechanisms and aids in the development of specific preventive strategies. This demonstrates the models' versatility in enhancing performance and reducing injury risks, highlighting the importance of biomechanical analysis in understanding the complex interplay between pianist biomechanics and injury prevention across diverse anthropometric profiles. Moreover, integrating biomechanical insights into piano pedagogy offers a new frontier in teaching methodologies. By incorporating findings on optimal playing techniques and body mechanics, educators can guide students toward healthier playing habits. This involves teaching strategies to improve posture, minimize strain through ergonomic movements, and embedding breaks and physical exercises into practice routines. Such an approach not only enhances performance but also proactively addresses the prevention of musculoskeletal disorders, making the learning process more sustainable and injury-free.

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