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RESEARCH ARTICLE

# Analysis of Force Profile Features in Spinal Manipulation Therapy

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This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the local ethics board of Kantonale Ethikkomission Zürich (KEK), and performed in line with the declaration of non-responsibility (Rew-2020-000932).

**ABSTRACT** Spinal manipulation therapy (SMT) is widely used as an intervention for musculoskeletal conditions. However, the automated detection and analysis of force profile features in SMT have received limited attention. This study aims to address this research gap by developing a toolbox for the automatic detection and annotation of force-time profile features in SMT. For validation purposes, we will investigate the correlation between these features and characteristics of patient vignettes. Force data was collected from 1233 SMT interventions using a commercially available pressure sensor. With the aggregation of three feature selection methods (Chi squared, MRMR, and ReliefF), the results indicate a significant increase in maximum thrust speed for mentally envisioned athletic male patients compared to elderly females ($p < 0.01$) . To the best of our knowledge, this study is the first of its kind, representing a pioneering exploration of automated force profile analysis in SMT. The findings hold immense potential to advance technology, support training of manual interventions, and facilitate the development of objective treatment feedback tools. The observed correlations between the extracted features and patient characteristics provide valuable insights for personalized SMT approaches.

**INDEX TERMS** Spinal manipulation therapy, force profile features, force-time profile, practitioner characteristics, optimization methods, chiropractic education, treatment feedback tools, personalized approaches.

## I. INTRODUCTION

Back pain is a prevalent issue affecting a significant portion of the global population. In 2019, approximately 39% of adults worldwide reported experiencing back pain [1]. The impact of back pain is particularly notable in the United States, where a staggering 80% of Americans encounter back pain at least once in their lifetimes [2]. It is crucial to recognize that back and neck pain not only cause personal discomfort but also pose substantial challenges in occupational settings. In fact, they are the leading cause of job-related disability and one of the primary reasons for missed work days [3].

To address the challenges associated with back and neck pain, various treatment approaches have been employed. Among them, spinal manipulation therapy (SMT) has emerged as a commonly utilized manual therapy technique, widely used amongst diffferent professions, e.g., manual medicine, physical therapy and chiropractic. SMT involves the application of high-velocity, low-amplitude forces to the spine, aiming to enhance spinal joint mobility and alleviate pain. Its applications span across multiple conditions, including back pain, neck pain, and headaches [4]. The force-time profile of SMT may play a critical role in determining its efficacy and safety [5].

Figure 1 illustrates the typical force-time profile of an SMT thrust, highlighting its four distinctive phases. Within the

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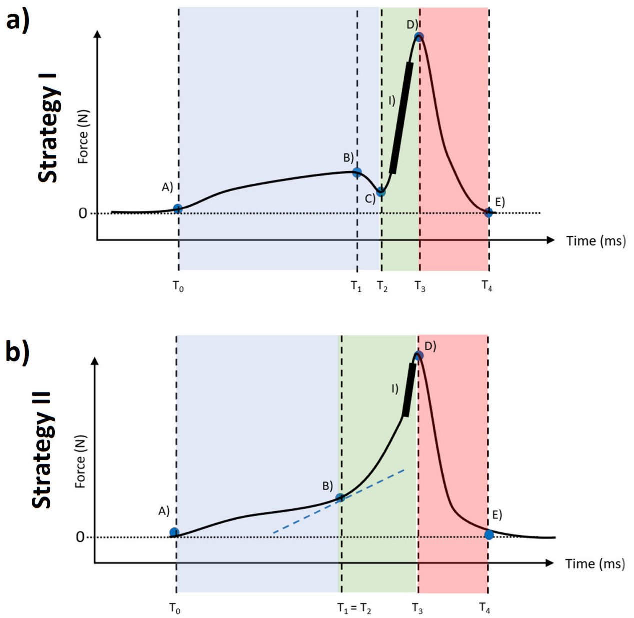

**FIGURE 1. Biomechanically distinctive force-time profiles: (a) Strategy I and (b) Strategy II [6].**

collected data set, two different force development strategies have been identified. Strategy I [6] in Figure 1a (around 80% of thrusts) includes a very constant preload, with the end of the preload phase usually accompanied by a brief decrease of preload force, referred to as the 'Downward incisural point' (DIP). Strategy II [6] in Figure 1b is characterized by a constantly increasing preload, which evolves to a thrust without a decrease of force at any time point. Here is a brief description of each phase depicted in Figure 1:

1) Phase 1 (Preload phase): the quasi-static load applied to the soft tissues overlaying the segment to be manipulated. Its purpose is to engage the soft tissue and to move the joint towards its physiological limit. In Figure 1(a,b), the profile segment between $T_0$ and $T_1$ visually represents this preload stage.
2) Phase 2 (DIP phase): the diminution of preload force just before the thrust, visually represented in Strategy I (Figure 1a). Note that the DIP does not usually occur in Strategy II (Figure 1b).
3) Phase 3 (Thrust Phase): the delivery of thrust immediately before the peak thrust force. In Figure 1(a,b), the thrust speed is measured between $T_2$ and $T_3$.
4) Phase 4 (Resolution phase): the force typically decreases gradually. In Figure 1(a,b), the profile segment between point $T_3$ and $T_4$ visually represents this peak.

During the DIP phase, there is a decrease or backing off of force. Clinicians generally consider this phase to be biomechanically undesirable because reducing force can have negative effects, such as reducing the specificity of the target area and causing tissue slackening [6]. It is important to maintain appropriate tension during the thrust without backing off or decreasing force to preserve the original position and tension of the tissues. This ensures the optimal effectiveness and precision of the thrust technique.

Various digital pressure sensing technologies can be used to quantify the force-time profiles of SMT. Force transducers and pressure sensors represent some examples of these sensing modalities. By leveraging these technologies, detailed insights regarding the magnitude, spatial distribution, and orientation of applied forces during SMT can be obtained. This comprehensive characterization of force dynamics contributes to a deeper understanding of the biomechanical aspects underlying SMT interventions. Moreover, the analysis of force-time profile can also help identify potential safety issues and inform the development of guidelines for safe and effective SMT practice [7].

Considerable research efforts have been dedicated to visualizing force-time profiles in the context of SMT [8]. However, there is a notable gap in the exploration of automated detection and analysis of force profile features, which play a crucial role in determining the effectiveness of manipulation interventions. Figure 1b demonstrates the absence of a DIP, indicating the merging of $T_1$ and $T_2$ into a single point. Consequently, the objective of this study was to develop a comprehensive toolbox for the automatic detection and annotation of force-time profile features measured during the delivery of thoracic spinal manipulation to human analogue manikins. Additionally, we aim to investigate the association between certain features and two fictious patient scenarios (a young very athletic male and an elderly, comparatively more fragile female patient), hypothesizing significant differences in force time features between two extreme cases. To the best of our knowledge, this study represents the first exploration in this domain. It has the potential to push this technology one step forward, impacting how chiropractic education is approached and facilitating the development of objective treatment feedback tools.

## II. METHODOLOGY

### A. STUDY SETTING AND PARTICIPANTS

Data collection took place during the 3-day annual Swiss chiropractic congress held in Lugano, Switzerland from September 1st to 3rd, 2022. Participating clinicians were assigned personal study IDs, which remained consistent throughout the entire study. The data collection process ensured anonymity, with no collection of health-related information or personal data. The study received a declaration of non-responsibility from the local ethics board, Kantonale Ethikkomission Zürich (KEK). A total of 1233 SMT interventions were collected.

### B. SMT INTERVENTIONS

All SMT interventions were conducted using a human manikin (HAM$^{TM}$, CMCC, Toronto, Canada), as shown in Figure 2.[1] Prior to data collection, participants were given

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[1] photo: courtesy of Luana Nyirö

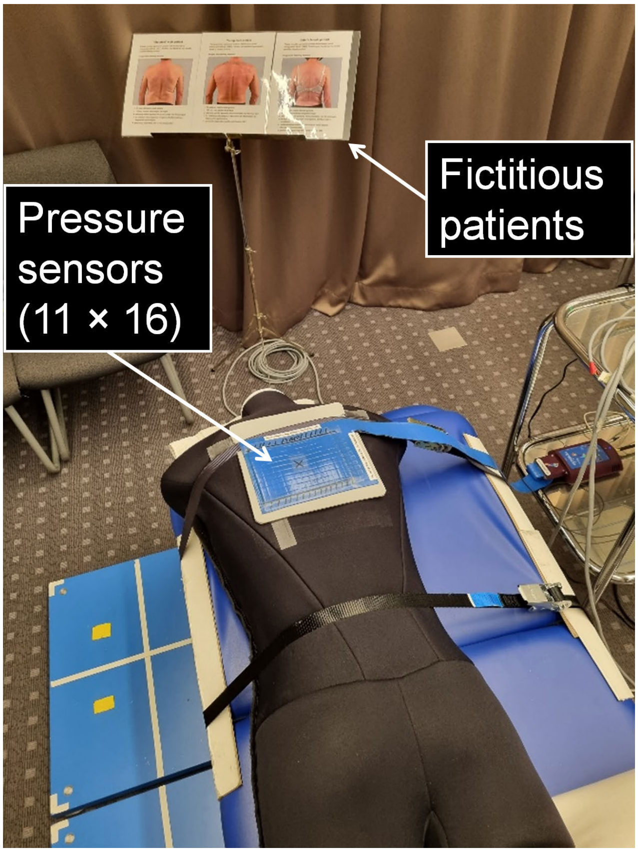

**FIGURE 2.** **Study set-up during data collection. Clinicians were presented with three patient vignettes, each accompanied by an image of the corresponding fictitious patient's back. The scenarios included a 50-year-old healthy male (reference), a 30-year-old healthy male athlete, and a 70-year-old healthy female, all described as returning patients with sporadic mid-thoracic pain.**

an opportunity to familiarize themselves with the set-up and palpation of the manikin. They performed three trial runs of SMT at a familiarization station that replicated the exact set-up used for data collection. Trained study assistants provided standardized instructions and supervised the familiarization process.

During data collection, participants were presented with three patient vignettes, each accompanied by an image of the corresponding fictitious patient's. These vignettes described specific scenarios, which were as follows:

- Scenario 1: 50-year-old healthy male (used as a reference scenario)
- Scenario 2: 30-year-old healthy male athlete
- Scenario 3: 70-year-old healthy female

All vignettes were described as a returning patient for sporadic musculoskeletal mid-thoracic pain.

After reviewing all scenarios, participants were instructed to perform three consecutive SMT interventions on the manikin for each scenario. Initially, all participants executed three thrusts for Scenario 1. The order of performing Scenarios 2 and 3 was randomized among participants. During the thrusts, participants were directed to visualize a patient corresponding to the described scenario presented in the vignette and perform the thrusts as closely as possible to their clinical routine. Following the data collection phase, participants were given the opportunity to provide feedback on their perception of the study set-up and subjectively rate the quality of the thrusts they delivered.

### C. MEASUREMENT DEVICE

Force-time profiles were captured using a flexible pressure-sensing pliance-xf-16 system (Novel, Munich, Germany) with an 11 × 16 sensor matrix providing a sensor density of 1 sensor/cm$^2$. The system was calibrated to measure peak loads up to 1.2 MPa and sampled the data at a rate of 100 Hz. The sensor validity, with a maximum error of 5%, was confirmed by the manufacturer and further validated in our laboratory against a force plate (Winterthur, Switzerland, 1000 Hz) as a reference standard prior to data collection.

### D. ANNOTATION OF PROFILES

#### 1) AUTOMATIC DETECTION

A derivative-based approach was employed to identify the four points of interest in the force-time profile. For $T_0$ and $T_4$, the first and last points with recorded data were selected, respectively, based on the finite difference change from zero amplitude to higher (in the case of $T_0$) or from higher amplitude to zero (in the case of $T_4$). For $T_3$, the point of peak force was chosen. To determine $T_2$, the program searched for the point with the maximum acceleration (maximum of the second derivative), then established a 0.06-second interval around that point and identified the minimum DIP within it. Finally, for $T_1$, the maximum point between $T_0$ and $T_2$ was selected. After applying this approach the following features were detected:

- $T_0$: first point with recorded force data that was connected to the peak force [2]
- $T_1$: local maximum, delimited by $T_0$ and $T_2$, with the condition of max. 0.5 seconds prior to peak force [3]
- $T_2$: maximum rate of thrust acceleration. The local minimum was determined within a ± 0.02-second interval, similar to Strategy I. If no local minimum was found, then the corresponding point of the maximum of the second derivative was considered as $T_2$. This sometimes resulted in the exact point as $T_1$, as shown in Figure 1b or slightly near it, as shown Figure 1a depending on the curvature of the DIP.
- $T_3$: point of recorded force with highest magnitude
- $T_4$: last point with recorded data connected to peak force
- Max. thrust speed: maximum of first derivative
- Thrust duration: time interval between $T_2$ and $T_3$

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[2] This condition was necessary because some of the profiles had recordings of force before the start of the preload, due to involuntary touching of the sensor or calibration errors.

[3] This condition was necessary because some profiles show a high preload force before adjustment to a smaller preload force.

- Preload impulse: area under the curve from $T_0$ to $T_2$
- Thrust impulse: area under the curve from $T_2$ to $T_3$
- Total impulse: area under the curve from $T_0$ to $T_4$

### 2) GRAPHICAL USER INTERFACE (GUI)

In addition to the automatic selection of the critical points of the profiles, a GUI was created to allow investigators to annotate the points manually (Figure 3). The importance of a tool of this kind lays in the lack of consensus in the definition of the points. With the help of this app, we will be able to collect data from different manual therapy professionals delivering SMT all over the world, to have as much input as possible regarding what clinicians deem to be the most important points. The app was designed on Matlab App Designer. The Chiropractor Annotation App, abbreviated as CAP, utilizes an automatic detection algorithm to suggest critical points, but investigators have the flexibility to manually select alternative points if desired. Any points manually chosen by the investigators, along with any additional comments, are then saved to an Excel sheet for further analysis.

## III. FEATURE IMPORTANCE

The final step involved assessing the importance of each feature in different types of thrusts. We focused on assessing feature correlation in SMT: differentiating profiles and features based on envisioned patient scenarios, with manikin-based thrusts. For each assessment, we applied three feature selection methods, as follows:

### 1) CHI SQUARE TEST

Chi squared is a statistical method used to determine the independence between two categorical variables. In feature selection, Chi squared is used to evaluate the relevance of each feature (variable) with respect to the target variable (in this case, differentiating envisioned patient scenario). The method measures the significance of the association between each feature and the target variable by comparing the observed frequency distribution with the expected distribution. Features with higher Chi squared values are considered more relevant and are selected for further analysis. In other words, the Chi squared feature selection method examines the statistical dependence between each predictor variable and the target variable (e.g., envisioned patient sex) using individual chi-square tests [9]. It calculates the chi-square test statistic ($x^2$) as the sum of squared differences between the observed ($O_i$) and expected ($E_i$) values divided by the expected value:

$$x^2 = \Sigma \frac{(O_i - E_i)^2}{E_i}, \tag{1}$$

where a small $p$ value obtained from the chi-square test indicates that the predictor variable is dependent on the response variable, suggesting its significance as an important feature.

### 2) MAXIMUM RELEVANCE MINIMUM REDUNDANCY (MRMR)

MRMR is a method used to select the most important features for a specific target variable while also avoiding redundant information among the selected features [10]. It considers the mutual information between each feature and the target variable, as well as the mutual information between different features. The main aim is to choose features that are highly relevant to the target variable while ensuring that they complement each other and do not duplicate information. By using MRMR, we can efficiently select a concise yet informative set of features for classification tasks, which is calculated as follow:

$$\mathrm{MRMR}(X) = \frac{1}{m}\sum_{i=1}^{m}[I(f_i, Y) - \frac{1}{k}\sum_{j=1}^{k} I(f_i, f_{S_j})], \tag{2}$$

$\mathrm{MRMR}(X)$ is the score for the feature set $X$, $m$ is the total number of features in the dataset, $f_i$ represents the i-th feature in the dataset $X$, $Y$ is the target variable, $I(f_i, Y)$ is the mutual information between the i-th feature $f_i$ and the target variable $Y$, $k$ is the number of previously selected features in the feature set $S$, $f_{S_j}$ represents the j-th feature in the previously selected feature set $S$, and $I(f_i, f_{S_j})$ is the mutual information between the i-th feature $f_i$ and the j-th feature $f_{S_j}$ in the feature set $S$.

The goal is to maximize the MRMR score, which indicates the balance between relevance to the target variable and redundancy among the selected features.

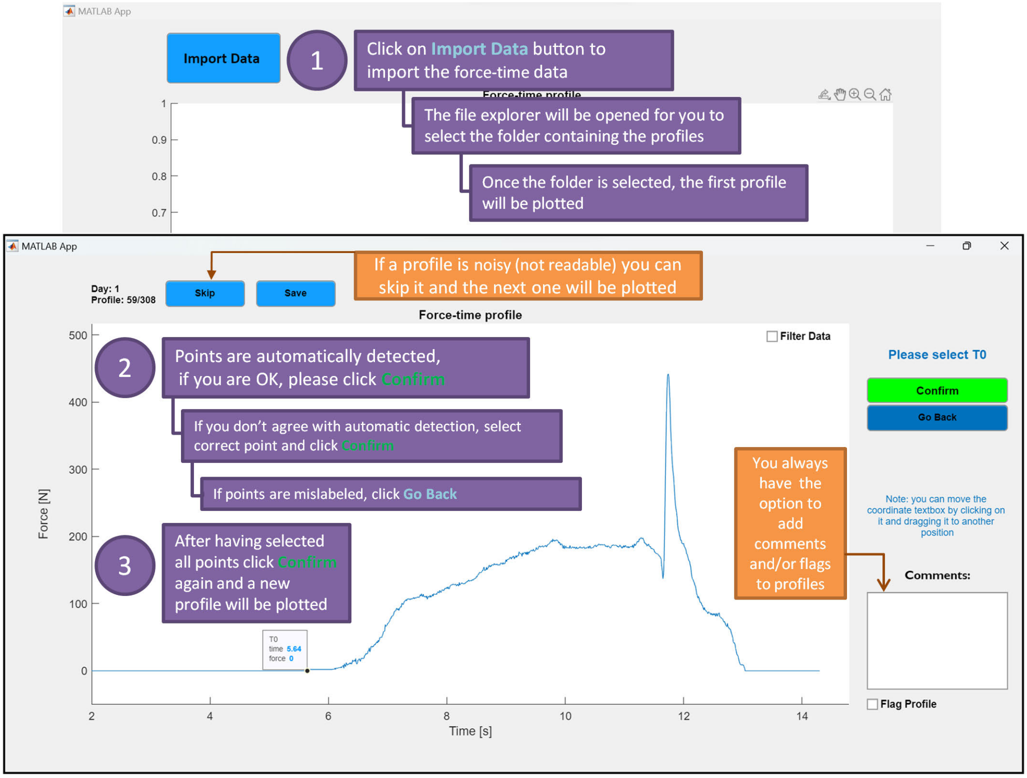
### 3) RELIEFF

ReliefF is a feature selection method designed for machine learning tasks, particularly for classification problems. It is based on the idea of nearest neighbor analysis and evaluates the relevance of features by considering how well they can discriminate between instances of different classes (in this case, patient sex). ReliefF computes the difference between the feature values of an instance and its nearest neighbors belonging to the same and different classes. Features that contribute significantly to distinguishing between different classes are selected as relevant.

The ReliefF algorithm penalizes predictors that give different values to neighbors of the same class and rewards predictors that give different values to neighbors of different classes [11]. Here, the response variable, such as envisioned patient sex, is considered in the determination of the nearest neighbors and the associated weights. By updating the weights based on the differences between observations and their nearest neighbors, the ReliefF algorithm identifies the predictors that contribute the most to distinguishing between different classes (e.g., male and female patients) and assigns them higher weights using mainly the following equation:

$$\mathrm{ReliefF}(f_i) = \frac{\sum_{j=1}^{k} \mathrm{diff}(f_i, T_{n_j})}{k}, \tag{3}$$

where $\mathrm{ReliefF}(f_i)$ is the ReliefF score of feature $f_i$, $k$ is the number of nearest neighbors (a parameter set by the user),



1 Click on Import Data button to import the force-time data

The file explorer will be opened for you to select the folder containing the profiles

Once the folder is selected, the first profile will be plotted

If a profile is noisy (not readable) you can skip it and the next one will be plotted

2 Points are automatically detected, if you are OK, please click Confirm

If you don't agree with automatic detection, select correct point and click Confirm

If points are mislabeled, click Go Back

3 After having selected all points click Confirm again and a new profile will be plotted

You always have the option to add comments and/or flags to profiles

Note: you can move the coordinate textbox by clicking on it and dragging it to another position

**FIGURE 3. The CAP App (Chiropractor Annotation App): A novel tool facilitating point annotation. This app empowers investigators to manually annotate critical points while also offering an automatic feature detection algorithm as a starting point. Clinicians can accept, modify, or add their own annotations based on their expertise and preferences. The app's significance lies in addressing the lack of consensus in defining critical points. By gathering input from manual therapy providers and clinicians worldwide, we aim to collect valuable data on essential points in spinal manipulation therapy practice. All selected points and any additional comments are conveniently saved to an Excel sheet for analysis and further insights.**

$\text{diff}(f_i, T_{n_j})$ represents the difference between the feature value of $f_i$ for the current instance and its value for the j-th nearest neighbor of the same class ($T_{n_j}$).

Each feature selection method offers a distinct mathematical perspective. These feature selection methods, namely Chi squared, MRMR, and ReliefF, were implemented using Matlab 2022b [12], [13]. To determine the averaged weight of each feature for each classification, the feature selection results from all three methods were averaged and normalized, which produced the ranking plot shown in Figure 4.

Note that the selection of Chi-squared, MRMR, and ReliefF methods for feature significance evaluation was driven by their distinct mathematical approaches and suitability for our analysis. Chi-squared is renowned for its effectiveness in evaluating categorical data, making it ideal for our scenario-based categorizations. MRMR offers a balance in selecting relevant yet non-redundant features, crucial for multidimensional data like ours. ReliefF's nearest neighbor analysis approach is particularly effective for classification tasks, aligning well with our study's objectives. The combination of these methods provided a robust and comprehensive analysis of feature importance.

## IV. RESULTS

Eighty-two clinicians delivered a total of 1233 thoracic spine manipulations. For these data, the most distinguishing characteristic for differentiating between thrusts performed on mentally envisioned patient scenarios was thrust speed. All three feature selection methods (Chi squared, MRMR, and ReliefF) consistently ranked thrust speed as the top characteristic, with an average normalized weight of 1. The bar chart clearly showed that a higher maximum thrust speed was applied to male patients compared to female patients, and this finding was statistically significant ($p$ value of 0.002, surpassing the threshold of 0.05), as shown in Figure 4.

In our analysis, we employed three distinct feature selection methods to robustly determine the most significant features in the force-time profiles. This methodology was akin to a majority voting system, where the primary goal was to discern features that were consistently ranked as highly significant by at least two of the three methods. Although our approach didn't involve a detailed tracking of the variability of each feature's ranking across different methods, we emphasized their consistency and agreement.

This methodology is exemplified in the analysis of features such as Max thrust speed. As depicted in Figure 4, Max

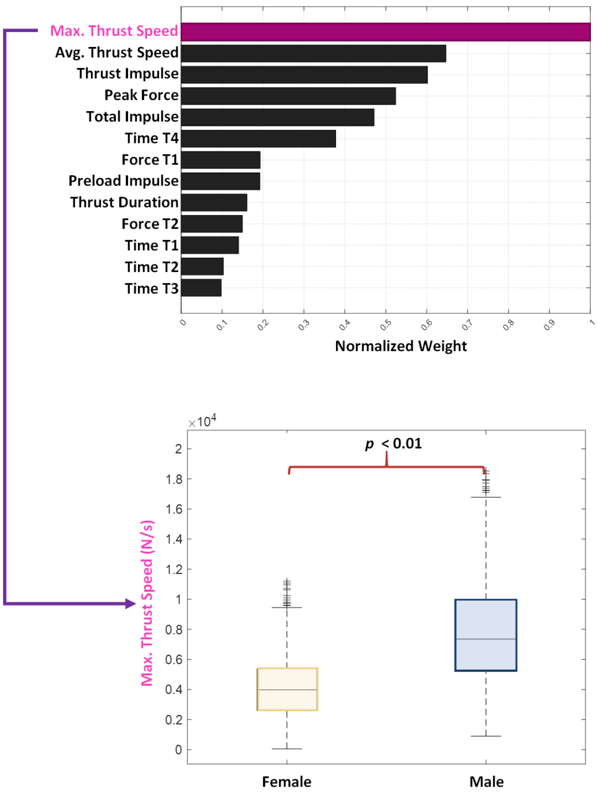


**FIGURE 4.** **Feature importance for mentally envisioned sex. The ranking weights of each feature are determined by averaging and normalizing the results obtained from three feature selection methods: Chi squared, MRMR, and ReliefF.**

thrust speed was a standout feature, ranking consistently in the top five in all three feature selection methods. This consistency underlines the feature's importance and reliability in characterizing force-time profiles in SMT. The convergence of multiple methods on the same set of features reinforces their relevance and supports the robustness of our findings.

## V. DISCUSSION

This study has several strengths. Firstly, the rigorous study setup and the standardized approach using a manikin ensure a high level of data comparability. However, this also leads to a limitation: the lack of tactile feedback to the clinician during both the preload and thrust phases.

The observed difference in maximum thrust speed between envisioned male and female patients may reflect inherent physiological and biomechanical variations between sexs, with males typically exhibiting greater muscle mass and strength [14]. This may influence the force exerted during SMT thrusts, leading chiropractors to intuitively adjust their thrust speed based on patient sex and perceived physical attributes.

Understanding the influence of thrust speed on sex differentiation allows chiropractors to optimize their treatment approaches, tailoring thrust speed based on patient sex for more effective and individualized care. Moreover, this finding opens avenues for future research exploring the relationship between thrust speed, patient sex, and treatment efficacy.

While thrust speed is a significant characteristic for sex differentiation, other factors may also contribute to the complexity of SMT thrusting techniques. Other features may exhibit varying degrees of relevance in differentiating between thrusts performed on envisioned male and female patients. Therefore, a comprehensive understanding of the interplay between multiple features can provide a more nuanced perspective on the biomechanical and physiological aspects of SMT thrusting.

Our study highlights thrust speed as a crucial factor in differentiating between SMT thrusts performed on mentally envisioned male and female patients. By considering the implications of thrust speed on sex differentiation, chiropractors can further enhance their clinical practice and deliver personalized and effective care to patients. Future research exploring the multifaceted relationship between thrust characteristics, patient attributes, and treatment outcomes can advance the field of SMT biomechanics and inform evidence-based practice. Additionally, further investigation into the influence of preload force on segmental biomechanics is warranted to optimize SMT techniques and enhance patient outcomes.

The most significant factor distinguishing between envisioned male and female patients is the maximum thrust speed. This finding aligns with intuition, as chiropractors often apply more force to envisioned male patients due to their typically stronger physique. A previous study [15], which used a robot to deliver forces (not a clinician), has established that the constant rate of force application has a notable impact on neuromuscular responses. It is essential to consider this difference, as the biomechanics of thrusts delivered by a robot differ from those delivered by a clinician, leading to potentially distinct physiological responses. The influence of thrust speed on neuromuscular responses is significant and underscores the importance of this characteristic in the context of SMT.

Furthermore, the influence of maximum thrust speed on sex differentiation is essential to consider in the context of patient comfort and treatment effectiveness. The findings suggest that chiropractors may naturally adjust their thrust speed based on patient sex, potentially impacting treatment outcomes and patient experiences. As such, understanding the relationship between thrust speed and patient sex can enhance chiropractic practice and contribute to individualized care.

Additionally, our results indicate that preload force does not play a significant role in characterizing force-time profiles. While one study suggests that preload force may modulate neuromuscular and biomechanical responses through changes in the rate of force application [16], there is limited information available in the current literature regarding the influence of preload force on segmental biomechanics. Further research is needed to elucidate this relationship fully.

The absence of a significant association between preload force and force-time profiles may have implications for treatment protocols and biomechanical considerations during spinal manipulations. Future studies exploring the effects of preload force on neuromuscular responses and segmental biomechanics can provide valuable insights into optimizing SMT techniques and enhancing patient outcomes. By delving deeper into these relationships, practitioners can refine their approaches and tailor treatments to individual patient needs, ensuring safe and effective clinical care.

To further enhance the understanding and accuracy of SMT force-time profiles, a future research step involves conducting a detailed statistical analysis to compare manual annotations of these profiles by different chiropractors. This will involve assessing the level of agreement and consistency among chiropractors in identifying critical points in the force-time profiles. Additionally, comparing these manual annotations with the outputs of our automated detection method will be crucial. Such a comparative analysis will not only shed light on the precision and reliability of our automated approach but will also offer valuable insights into its effectiveness compared to traditional manual methods. This step is pivotal in validating and refining our model for broader clinical application.

## VI. CONCLUSION

This study developed a toolbox for automated detection and annotation of force-time profiles in SMT, filling a research gap. Analyzing data from 1000+ SMT interventions, notable findings emerged: mentally envisioned males were treated with significantly higher maximum thrust speed than females. This pioneering exploration of automated force profile analysis in SMT has transformative potential for technology, chiropractic education, and objective treatment feedback tools. The observed correlations between extracted features and patient characteristics provide valuable insights for personalized SMT approaches.

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## REFERENCES

[1] J. W. Lucas, E. M. Connor, and J. Bose, "Back, lower limb, and upper limb pain among us adults, 2019," Nat. Center Health Statist., Hyattsville, MD, USA, Tech. Rep. 415, 2021.

[2] R. S. D'Souza, M. Y. Jin, and A. Abd-Elsayed, "Peripheral nerve stimulation for low back pain: A systematic review," *Current Pain Headache Rep.*, vol. 27, no. 5, pp. 117–128, May 2023.

[3] J. M. Fritz, E. Lane, M. McFadden, G. Brennan, J. S. Magel, A. Thackeray, K. Minick, W. Meier, and T. Greene, "Physical therapy referral from primary care for acute back pain with sciatica: A randomized controlled trial," *Ann. Internal Med.*, vol. 174, no. 1, pp. 8–17, Jan. 2021.

[4] P. G. Shekelle, A. H. Adams, M. R. Chassin, E. L. Hurwitz, and R. H. Brook, "Spinal manipulation for low-back pain," *Ann. Internal Med.*, vol. 117, no. 7, pp. 590–598, 1992.

[5] M. Pasquier, C. Daneau, A.-A. Marchand, A. Lardon, and M. Descarreaux, "Spinal manipulation frequency and dosage effects on clinical and physiological outcomes: A scoping review," *Chiropractic Manual Therapies*, vol. 27, no. 1, pp. 1–12, Dec. 2019.

[6] G. Gyer, J. Michael, J. Inklebarger, and I. Ibne Alam, "Effects of biomechanical parameters of spinal manipulation: A critical literature review," *J. Integrative Med.*, vol. 20, no. 1, pp. 4–12, Jan. 2022.

[7] C. Stevinson and E. Ernst, "Risks associated with spinal manipulation," *Amer. J. Med.*, vol. 112, no. 7, pp. 566–571, May 2002.

[8] L. M. Gorrell, L. Nyirö, M. Pasquier, I. Pagé, N. R. Heneghan, P. Schweinhardt, and M. Descarreaux, "Spinal manipulation characteristics: A scoping literature review of force-time characteristics," *Chiropractic Manual Therapies*, vol. 31, no. 1, pp. 1–15, Sep. 2023.

[9] H.-Y. Kim, "Statistical notes for clinical researchers: Chi-squared test and Fisher's exact test," *Restorative Dentistry Endodontics*, vol. 42, no. 2, pp. 152–155, 2017.

[10] J. R. Berrendero, A. Cuevas, and J. L. Torrecilla, "The mRMR variable selection method: A comparative study for functional data," *J. Stat. Comput. Simul.*, vol. 86, no. 5, pp. 891–907, Mar. 2016.

[11] R. J. Urbanowicz, M. Meeker, W. La Cava, R. S. Olson, and J. H. Moore, "Relief-based feature selection: Introduction and review," *J. Biomed. Informat.*, vol. 85, pp. 189–203, Sep. 2018.

[12] G. Roffo, "Feature selection library (MATLAB toolbox)," 2016, *arXiv:1607.01327*.

[13] S. Yu, Z. Zhang, X. Liang, J. Wu, E. Zhang, W. Qin, and Y. Xie, "A MATLAB toolbox for feature importance ranking," in *Proc. Int. Conf. Med. Imag. Phys. Eng. (ICMIPE)*, Nov. 2019, pp. 1–6.

[14] J. L. Nuzzo, "Narrative review of sex differences in muscle strength, endurance, activation, size, fiber type, and strength training participation rates, preferences, motivations, injuries, and neuromuscular adaptations," *J. Strength Conditioning Res.*, vol. 37, no. 2, pp. 494–536, 2023.

[15] F. Nougarou, I. Pagé, M. Loranger, C. Dugas, and M. Descarreaux, "Neuromechanical response to spinal manipulation therapy: Effects of a constant rate of force application," *BMC Complementary Alternative Med.*, vol. 16, no. 1, pp. 1–8, Dec. 2016.

[16] F. Nougarou, C. Dugas, M. Loranger, I. Pagé, and M. Descarreaux, "The role of preload forces in spinal manipulation: Experimental investigation of kinematic and electromyographic responses in healthy adults," *J. Manipulative Physiol. Therapeutics*, vol. 37, no. 5, pp. 287–293, Jun. 2014.

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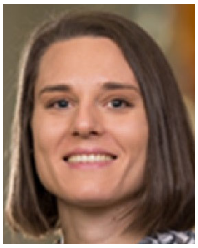

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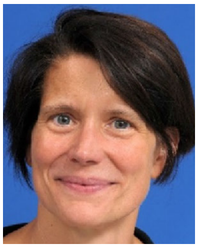

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