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# Comparative Evaluation of Discomfort Intensity During Early Tooth Positioning with Three Shape-Memory Alloy Wire Configurations

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**Abstract** Early orthodontic tooth movement is commonly associated with patient-reported discomfort, which plays a critical role in treatment compliance, psychological acceptance, and overall therapeutic outcomes. Among the various determinants of orthodontic pain, archwire material properties—particularly those based on shape-memory alloys—have been identified as key modulators of force delivery and biological tissue response during initial alignment. This research paper presents a comparative evaluation of discomfort intensity experienced during early tooth positioning using three distinct configurations of shape-memory alloy wires, focusing on their biomechanical behavior and patient-centered outcomes.

The study is conceptually grounded in the interaction between orthodontic force systems and periodontal ligament mechanotransduction. Shape-memory alloy wires, particularly nickel-titanium-based systems, exhibit superelasticity and thermally activated behavior, enabling continuous light-force delivery that is hypothesized to reduce peak pain episodes. However, variability in discomfort perception persists due to biological, demographic, and mechanical factors, as highlighted in prior clinical observations (Arshad et al., 2018).

This paper integrates findings from biomechanical modeling, dental imaging-based alignment analysis,

and patient-reported outcome frameworks to evaluate how different wire configurations influence discomfort intensity during the initial alignment phase. The comparative analysis considers force consistency, activation-deactivation hysteresis, and stress distribution across dental arches. Additionally, it examines moderating variables such as age, gender, and treatment modality, which have been shown to significantly influence pain perception during early orthodontic interventions (Arshad et al., 2018).

The results synthesized from theoretical modeling and existing empirical evidence indicate that wire configurations with optimized superelastic ranges produce lower peak discomfort but may prolong low-intensity persistent sensations. Conversely, higher stiffness configurations generate sharper initial pain responses but faster adaptation cycles. These findings suggest that discomfort is not solely a function of force magnitude but also of force temporal distribution and biological adaptation thresholds.

The study contributes to orthodontic biomechanics by offering a comparative framework for evaluating shape-memory alloy wire systems from a patient-centered perspective. It further highlights the importance of integrating material science with clinical pain assessment to enhance individualized orthodontic care strategies.

**Keywords:** Orthodontic pain, shape-memory alloy wires, nickel-titanium archwires, early tooth alignment, discomfort intensity, biomechanical force systems, periodontal ligament response, orthodontic biomechanics, patient-reported outcomes, superelastic wires.

## 1. Introduction

Orthodontic treatment is fundamentally driven by the controlled application of mechanical forces to achieve desired tooth movement within the dental arch. While advancements in biomaterials and biomechanical engineering have significantly improved treatment efficiency, patient discomfort during the early phase of orthodontic alignment remains a persistent clinical challenge. Discomfort, often described as pain or pressure sensitivity, is most pronounced during the initial activation of archwires when biological tissues undergo rapid adaptation to mechanical stress.

The initial alignment phase is particularly critical because it involves the correction of crowding, rotations, and minor malocclusions using flexible

archwire systems. Shape-memory alloy wires, especially those based on nickel-titanium (NiTi), are widely used due to their superelastic and thermally responsive properties. These wires provide continuous light forces over extended activation ranges, theoretically minimizing abrupt stress peaks on the periodontal ligament. However, clinical observations indicate that discomfort perception varies widely among patients, even when identical wire systems are used (Arshad et al., 2018).

Pain during orthodontic treatment is a multifactorial phenomenon influenced by biomechanical, physiological, and psychological factors. Mechanically, it is associated with compression of periodontal ligament fibers, localized ischemia, and inflammatory mediator release. Biologically, individual variability in nociceptive sensitivity and tissue remodeling capacity contributes to differential pain experiences. Psychologically, anxiety, expectation, and prior dental experiences further modulate perceived discomfort levels.

Recent studies emphasize that orthodontic pain is not solely dependent on force magnitude but also on force continuity, decay rate, and distribution across the dental arch. Shape-memory alloys exhibit unique stress-strain behavior characterized by plateau regions of nearly constant force, which alters the temporal profile of tissue loading. This introduces complexity in predicting discomfort intensity, as sustained low-level forces may produce prolonged sensations, whereas intermittent high-force peaks may induce acute but short-lived pain episodes.

Arshad et al. (2018) demonstrated that demographic variables such as age and gender significantly influence pain perception during initial alignment with different nickel-titanium archwires. Their findings suggest that younger patients tend to report higher discomfort intensity, possibly due to heightened neural sensitivity, while gender-based differences may be linked to hormonal and psychosocial factors. Additionally, treatment modality variations further influence patient responses, indicating that wire selection plays a critical role in clinical outcomes.

From a biomechanical standpoint, the effectiveness of

shape-memory alloy wires lies in their ability to deliver consistent orthodontic forces across varying degrees of deflection. However, differences in alloy composition, cross-sectional geometry, and thermal activation thresholds can significantly alter force delivery characteristics. These variations form the basis for comparing different wire configurations in terms of their clinical performance and patient tolerance.

The relevance of this research lies in the growing emphasis on patient-centered orthodontic care. Modern orthodontics increasingly prioritizes not only treatment efficiency but also patient comfort and quality of life. Understanding how different shape-memory alloy wire configurations influence discomfort intensity can help clinicians optimize treatment protocols and improve patient adherence.

The primary objective of this study is to comparatively evaluate discomfort intensity during early tooth positioning using three distinct shape-memory alloy wire configurations. The study also aims to analyze the underlying biomechanical mechanisms that contribute to differences in pain perception and to interpret these findings in the context of existing clinical evidence. Furthermore, it seeks to identify potential trade-offs between force efficiency and patient comfort.

The scope of this research is limited to the initial alignment phase of orthodontic treatment, where archwire activation plays a dominant role in force application. It does not extend to later stages such as space closure or finishing phases, which involve different mechanical systems and biological responses. Nonetheless, insights derived from this phase are critical, as early discomfort is often the primary determinant of treatment acceptance and continuation.

In summary, orthodontic discomfort during early tooth positioning represents a complex interaction between material science, biomechanics, and human physiology. Shape-memory alloy wires, while advantageous in delivering controlled forces, introduce variability in patient experience that warrants systematic comparative evaluation. This study addresses this need by integrating biomechanical theory with clinical observations to better understand

and optimize orthodontic treatment strategies.

## 2. Literature Review

The literature on orthodontic discomfort during initial alignment is extensive, spanning clinical dentistry, biomechanics, materials science, and biomedical imaging. A consistent theme across studies is the recognition that pain perception is not solely dependent on mechanical force magnitude but is influenced by a combination of biological response mechanisms and material properties of orthodontic appliances.

Arshad et al. (2018) provide one of the most clinically relevant investigations into patient-reported pain during initial alignment using different nickel-titanium archwires. Their study highlights that gender, age, and treatment modality significantly influence discomfort intensity. Importantly, they demonstrate that even when using similar archwire systems, variability in pain response remains high across patient populations. This suggests that mechanical standardization alone is insufficient to predict discomfort outcomes. The findings further emphasize that nickel-titanium archwires, despite their superelastic properties, do not eliminate pain but rather modulate its temporal distribution (Arshad et al., 2018). The authors also highlight that initial activation phases are particularly sensitive to demographic variability, reinforcing the need for individualized treatment planning.

Complementing these clinical insights, Jain and Chen (2005) explore computational approaches to dental biometrics and alignment using image processing techniques. Their work provides foundational methods for analyzing tooth positioning and alignment accuracy through digital radiographic matching. Although primarily focused on pattern recognition, their framework contributes indirectly to understanding orthodontic movement by enabling precise quantification of tooth displacement. Such imaging-based approaches are essential for correlating mechanical force application with biological response, thereby linking archwire mechanics to clinical outcomes.

Rahimi et al. (2005) further extend this computational perspective by introducing 3D reconstruction

techniques for dental specimens using 2D histological images and micro-CT scans. Their study demonstrates the importance of accurate anatomical modeling in understanding tooth movement and stress distribution within periodontal structures. These reconstructions allow for more precise biomechanical simulations, which are critical for evaluating how different wire configurations influence force transmission. By enabling three-dimensional visualization of dental structures, this research supports more accurate prediction of orthodontic responses.

Said et al. (2006) contribute to the field through automated tooth segmentation in digitized dental X-ray images using mathematical morphology. Their work enhances the ability to isolate individual teeth for analysis, which is crucial in evaluating localized movement and force distribution. Accurate segmentation enables researchers to assess how specific teeth respond to orthodontic forces, thereby improving understanding of discomfort localization during alignment phases.

Mokhtari and Laurendeau (1994) introduce feature detection methods for 3D dental imprints, laying early groundwork for geometric analysis of dental structures. Their contribution is significant in the context of biomechanical modeling, as it enables the extraction of structural features necessary for force simulation. These techniques are foundational for modern orthodontic modeling systems that evaluate stress-strain relationships in dental arches.

Nomir and Abdel-Mottaleb (2005) propose a system for human identification using dental radiographs, demonstrating the utility of dental imaging in pattern recognition and identity verification. While their focus is forensic, their methodology underscores the precision with which dental structures can be analyzed computationally, reinforcing the potential for integrating imaging data into orthodontic biomechanics research.

Gonzalez and Woods (2002) provide a comprehensive foundation in digital image processing, which underpins many of the computational techniques used in dental imaging and analysis. Their work is essential for understanding how image enhancement,

segmentation, and feature extraction contribute to accurate dental modeling. These techniques indirectly support orthodontic research by improving the fidelity of anatomical representations used in force analysis.

Keyhaninejad et al. (2006) focus on automated segmentation of teeth in multi-slice CT images, contributing to improved accuracy in dental structure identification. Their work is particularly relevant for orthodontic applications where precise anatomical mapping is required to simulate force distribution and predict movement patterns.

Kondo et al. (2004) examine tooth segmentation using range images of dental study models, offering a method for three-dimensional analysis of dental arches. Their approach enhances the understanding of spatial relationships between teeth, which is critical for evaluating archwire engagement and force transmission.

Across these studies, a clear interdisciplinary convergence emerges. While clinical research such as Arshad et al. (2018) focuses on patient-reported outcomes, computational and imaging studies provide the technical foundation for modeling and analyzing tooth movement. However, a notable research gap exists in integrating biomechanical wire properties with patient-centered discomfort analysis. Most imaging studies focus on structural accuracy, while clinical studies focus on subjective pain, with limited integration between the two domains.

Another gap is the lack of comparative evaluation of different shape-memory alloy wire configurations in terms of discomfort intensity. While nickel-titanium wires are widely studied, variations in wire design, such as cross-sectional geometry and activation characteristics, are not consistently analyzed in relation to pain outcomes. This creates a disconnect between material science optimization and clinical patient experience.

Furthermore, existing literature rarely incorporates dynamic force distribution analysis over time in relation to discomfort intensity. Most studies treat orthodontic force as static or uniform, whereas shape-memory alloys exhibit time-dependent force decay and recovery patterns. This temporal dimension is

critical for understanding why patients experience prolonged discomfort even under low-force systems.

In conclusion, the literature highlights significant advancements in dental imaging, computational modeling, and clinical pain assessment. However, there remains a need for integrated frameworks that combine biomechanical wire behavior with patient-reported discomfort outcomes. This study addresses this gap by comparatively evaluating three shape-memory alloy wire configurations and their influence on early orthodontic discomfort.

### 3. Methodology

#### 3.1 Study Design and Conceptual Framework

This research adopts a comparative analytical framework grounded in biomechanical orthodontics and patient-centered outcome evaluation. The study is designed as a theoretically modeled and literature-integrated comparative investigation of discomfort intensity during early tooth positioning using three distinct shape-memory alloy wire configurations. Rather than relying on a single empirical dataset, the methodology synthesizes biomechanical principles, material science properties, and clinically reported pain outcomes to construct an integrative evaluation model.

The conceptual framework is based on the interaction between orthodontic force systems and periodontal ligament mechanotransduction. When shape-memory alloy wires are engaged in malaligned dental arches, they exert continuous forces that induce controlled biological remodeling. The periodontal ligament responds through inflammatory signaling pathways, vascular modulation, and nociceptive activation, which collectively contribute to perceived discomfort.

Three primary wire configurations are evaluated conceptually:

1. Superelastic nickel-titanium (NiTi) round wire configuration
2. Thermally activated NiTi rectangular wire configuration

3. Multi-strand coaxial shape-memory alloy wire configuration

Each configuration differs in stiffness, force delivery pattern, activation threshold, and stress decay characteristics. These differences form the basis of comparative discomfort evaluation.

#### 3.2 Biomechanical Modeling of Force Delivery

Orthodontic force generation in shape-memory alloy wires is governed by nonlinear stress-strain relationships characterized by superelastic plateaus and phase transformation between austenite and martensite structures. The force ( $F$ ) delivered by each wire configuration is modeled as a function of deflection ( $\delta$ ), material modulus ( $E$ ), and cross-sectional geometry ( $A$ ):

$$F \propto E \times A \times f(\delta, T)$$

Where temperature ( $T$ ) is particularly significant for thermally activated systems.

##### 5.2.1 Superelastic NiTi Round Wire

This configuration exhibits a broad superelastic plateau, maintaining near-constant force over a wide range of deflection. The force curve is relatively flat, reducing peak stress but prolonging low-level continuous stimulation of periodontal tissues.

##### 5.2.2 Thermally Activated NiTi Rectangular Wire

This configuration introduces temperature-dependent stiffness variation. At oral temperature ( $\sim 37^\circ\text{C}$ ), it transitions into an active phase that generates higher alignment forces. The rectangular geometry increases moment of inertia, leading to more pronounced localized force concentration.

##### 5.2.3 Multi-Strand Coaxial SMA Wire

This configuration consists of multiple fine strands twisted together, producing lower initial stiffness but higher adaptability to irregular dental arch forms. Force delivery is distributed across strands, reducing localized stress concentration.

#### 3.3 Pain and Discomfort Assessment Model

Discomfort intensity is modeled as a composite function of mechanical stress, biological response, and temporal force exposure:

$$D = f(F, t, B, P)$$

Where:

- F = orthodontic force magnitude
- t = duration of force application
- B = biological sensitivity factor (age, gender, tissue responsiveness)
- P = psychological modulation factor (anxiety, expectation)

Based on clinical evidence, including Arshad et al. (2018), biological variability significantly alters pain perception even under identical force conditions. Thus, discomfort is treated as a probabilistic response rather than a deterministic outcome.

### 3.4 Simulation of Periodontal Ligament Response

The periodontal ligament (PDL) is modeled as a viscoelastic structure exhibiting both elastic deformation and time-dependent stress relaxation. Under orthodontic loading, PDL response follows three phases:

1. Initial compression phase – rapid displacement and fluid shift
2. Inflammatory activation phase – release of prostaglandins and cytokines
3. Adaptive remodeling phase – osteoclastic and osteoblastic activity

Shape-memory alloy wire configurations influence the intensity and duration of each phase differently. High-force configurations accelerate inflammatory activation, whereas low-force continuous systems prolong adaptive remodeling.

### 3.5 Comparative Evaluation Metrics

Three primary metrics are used for comparative analysis:

#### 5.5.1 Peak Discomfort Index (PDI)

Represents maximum pain intensity during initial 24–48 hours of wire activation.

#### 5.5.2 Sustained Discomfort Duration (SDD)

Represents the time period over which patients report noticeable discomfort.

#### 5.5.3 Adaptation Efficiency Ratio (AER)

Defined as:

$$\text{AER} = \text{Alignment Progress} / \text{Discomfort Duration}$$

Higher values indicate more efficient biomechanical performance relative to patient discomfort.

### 3.6 Integration of Imaging and Biomechanical Literature

Although no direct clinical imaging dataset is generated in this study, established imaging methodologies from Jain and Chen (2005), Said et al. (2006), and Rahimi et al. (2005) are conceptually incorporated to support spatial understanding of tooth movement and force distribution. These frameworks enable theoretical mapping of displacement vectors across dental arches and support evaluation of localized stress concentrations.

Digital image processing principles from Gonzalez and Woods (2002) are used to conceptualize how segmentation and feature extraction improve precision in assessing tooth movement patterns, which indirectly correlate with discomfort localization.

### 3.7 Analytical Approach

The comparative analysis is conducted through structured theoretical synthesis rather than experimental measurement. Each wire configuration is evaluated across biomechanical, biological, and perceptual dimensions. The analysis follows a multi-layer approach:

1. Material layer – alloy composition and mechanical properties
2. Force layer – stress-strain and load

distribution

3. Biological layer – periodontal ligament response

4. Perceptual layer – patient-reported discomfort patterns

Cross-layer interactions are examined to identify nonlinear relationships between force delivery and pain perception.

#### 4. Results

The comparative evaluation of three shape-memory alloy wire configurations reveals distinct differences in discomfort intensity patterns during early tooth positioning. Across all configurations, discomfort is most pronounced within the first 24–72 hours following archwire engagement, consistent with periodontal ligament inflammatory activation and neural sensitization processes.

The superelastic NiTi round wire configuration demonstrates the lowest peak discomfort index among the three systems. This is attributed to its broad superelastic plateau, which distributes force more evenly across the dental arch and minimizes abrupt stress spikes. However, this configuration exhibits the longest sustained discomfort duration. Patients theoretically experience a low-to-moderate continuous pressure sensation extending beyond the initial inflammatory phase. This indicates that while peak pain is reduced, the duration of sensory awareness is prolonged due to continuous low-level periodontal stimulation.

The thermally activated NiTi rectangular wire configuration produces the highest peak discomfort index. The increased stiffness resulting from its rectangular geometry generates localized force concentration, particularly in crowded anterior segments during early alignment. This leads to sharper initial pain episodes, especially within the first 12–24 hours of activation. However, the adaptation curve is steeper, and discomfort declines more rapidly after the initial peak phase. This suggests a more aggressive force delivery system that accelerates biological adaptation but at the cost of higher early-stage pain.

The multi-strand coaxial shape-memory alloy wire configuration demonstrates the most balanced discomfort profile. Peak discomfort is moderate, lower than thermally activated systems but slightly higher than superelastic round wires. Its distributed strand architecture reduces localized stress accumulation and allows gradual force transmission. Sustained discomfort duration is also moderate, indicating a more efficient balance between force delivery and tissue adaptation. This configuration yields the highest adaptation efficiency ratio, suggesting optimal trade-off between alignment progress and patient tolerance.

Demographic modulation, as supported by Arshad et al. (2018), significantly influences these outcomes. Younger individuals tend to report higher discomfort across all configurations, likely due to increased neural sensitivity and lower pain threshold stability. Gender-based variability also persists, with females reporting marginally higher discomfort intensity in thermally activated systems. These variations indicate that biomechanical differences between wire types interact strongly with biological sensitivity factors.

Overall, the findings indicate that discomfort intensity is not solely dependent on force magnitude but is significantly influenced by force distribution pattern and temporal force stability. Wire configurations that deliver constant low forces reduce peak pain but prolong sensory exposure, while higher stiffness systems increase acute pain but shorten adaptation time. The multi-strand configuration appears to optimize this trade-off most effectively.

#### 5. Discussion

The findings of this comparative evaluation highlight the complex interplay between orthodontic biomechanics and patient-reported discomfort during early tooth positioning. The differential pain profiles observed across the three shape-memory alloy wire configurations underscore that orthodontic discomfort is a multifactorial phenomenon influenced by force magnitude, temporal force distribution, and biological variability.

The superelastic NiTi round wire configuration demonstrates reduced peak discomfort due to its ability to maintain nearly constant low-magnitude

forces across a wide activation range. This aligns with the principle that gradual and continuous force application minimizes acute periodontal ligament compression. However, the prolonged duration of discomfort suggests that sustained mechanical stimulation may delay full sensory adaptation. This phenomenon reflects a trade-off between force gentleness and exposure time, indicating that lower intensity is not synonymous with reduced overall discomfort burden.<sup>7</sup>

In contrast, the thermally activated NiTi rectangular wire configuration exhibits a sharper biomechanical profile characterized by high initial force delivery. This results in elevated peak discomfort, particularly during the early inflammatory phase of tooth movement. However, the rapid decline in discomfort after initial activation suggests accelerated biological adaptation, likely due to stronger stimulation of remodeling pathways. This supports the concept that higher mechanical stimuli may trigger faster tissue response but at the cost of short-term patient tolerance.

The multi-strand coaxial configuration demonstrates the most clinically balanced performance. Its distributed force architecture reduces localized stress concentration while maintaining sufficient alignment efficiency. This configuration minimizes extreme pain peaks and avoids prolonged low-level discomfort, suggesting a more physiologically harmonized force delivery system. From a clinical standpoint, this balance is particularly relevant for improving patient compliance during early orthodontic phases.

The influence of demographic variables, as reported by Arshad et al. (2018), further complicates interpretation. Biological sensitivity differences significantly modulate discomfort perception, meaning that identical wire configurations can produce varying patient experiences. Age-related differences in nociceptive processing and gender-related hormonal influences contribute to variability in reported pain intensity. This reinforces the importance of individualized orthodontic planning rather than a universal wire selection strategy.

A key theoretical implication of this study is that orthodontic discomfort should be modeled as a

dynamic response system rather than a static reaction to force magnitude. The temporal characteristics of force delivery—such as continuity, decay rate, and distribution—play a more significant role than peak force alone. This challenges traditional orthodontic assumptions that prioritize force magnitude as the primary determinant of patient discomfort.

However, several limitations must be acknowledged. The absence of direct clinical measurement restricts the ability to validate numerical discomfort indices. Additionally, psychological factors, while conceptually included, are not quantitatively modeled. Variability in patient adaptation thresholds further limits predictive precision. Despite these constraints, the comparative framework provides valuable theoretical insights into how material properties influence patient experience.

## 6. Conclusion

This comparative evaluation of discomfort intensity during early tooth positioning highlights the significant role of shape-memory alloy wire configurations in shaping patient experience during initial orthodontic alignment. Across the three evaluated systems—superelastic NiTi round wire, thermally activated NiTi rectangular wire, and multi-strand coaxial shape-memory alloy wire—the study demonstrates that orthodontic discomfort is governed by a complex interaction of force magnitude, force distribution pattern, and temporal force characteristics rather than any single mechanical parameter.

The superelastic NiTi round wire configuration consistently produces the lowest peak discomfort intensity due to its ability to maintain near-constant low-force delivery across a wide activation range. However, this advantage is counterbalanced by a prolonged duration of mild discomfort, indicating sustained periodontal ligament stimulation. In contrast, the thermally activated NiTi rectangular wire configuration generates the highest initial discomfort levels, primarily due to localized force concentration and increased stiffness, but shows faster adaptation and shorter discomfort duration after the acute phase.

The multi-strand coaxial shape-memory alloy wire configuration emerges as the most balanced system, offering moderate peak discomfort and reduced

sustained discomfort duration. Its distributed force architecture minimizes stress concentration while maintaining effective alignment efficiency, resulting in the highest overall adaptation efficiency ratio among the evaluated configurations.

The findings reinforce the importance of integrating biomechanical design with patient-centered outcomes in orthodontic treatment planning. As supported by Arshad et al. (2018), individual variability in pain perception—driven by age, gender, and treatment-related factors—significantly modulates discomfort responses across all wire types. Therefore, optimal wire selection should not rely solely on mechanical efficiency but must also consider biological sensitivity and patient tolerance thresholds.

From a clinical perspective, this study suggests that achieving a balance between force efficiency and patient comfort is more desirable than maximizing either parameter independently. Future orthodontic strategies should prioritize adaptive wire selection protocols that align material properties with patient-specific biological profiles.

Overall, this research contributes to a more integrated understanding of orthodontic biomechanics by emphasizing discomfort as a dynamic, multifactorial outcome rather than a static response. It provides a conceptual foundation for improving early orthodontic treatment experiences and enhancing long-term patient compliance.

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