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Design Analysis of an Adjustable Road Bicycle Stem Based on Ergonomics and Biomechanics

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Abstract

Road bicycles are designed to achieve aerodynamic efficiency through a forward-leaning riding posture. Although this position can improve cycling performance, it may also increase biomechanical loading and the risk of musculoskeletal complaints when it is not aligned with the rider's anthropometric characteristics. The limited adjustability of conventional bicycle stems further restricts riders from achieving a more ergonomic riding position. This study investigated the ergonomic and biomechanical performance of an adjustable road bicycle stem developed to provide greater flexibility in handlebar positioning. A comparative experimental design was employed involving 30 road cyclists, with measurements conducted before using the standard stem and after using the adjustable stem prototype. Riding posture was assessed using motion capture to determine trunk flexion angle, while biomechanical loading was evaluated by calculating trunk moment. Ergonomic performance was assessed using the SNI 9011 questionnaire for musculoskeletal complaints. The adjustable stem increased the mean trunk flexion angle from 30.73° to 52.90° and reduced the average trunk moment from 193.94 Nm to 136.13 Nm. Participants also reported lower musculoskeletal complaint risk following use of the prototype. These findings suggest that the adjustable stem offers a more adaptable riding position and contributes to improved ergonomic performance by reducing biomechanical loading. The study provides evidence that incorporating ergonomic and biomechanical considerations into bicycle stem design can support the development of road bicycle components that better accommodate variations in rider characteristics.

Keywords: Adjustable stem, Bicycle ergonomics, Biomechanics, Motion capture.

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1. Introduction

Road bicycles are designed to achieve high riding performance by combining lightweight components, aerodynamic geometry, and an efficient riding posture. Compared with recreational bicycles, road bicycles require riders to adopt a lower and more forward-leaning posture to minimise aerodynamic drag and improve cycling efficiency [15], [18]. Although this posture offers performance advantages, prolonged riding in an excessive forward position may increase mechanical loading on the neck, shoulders, and lower back, potentially leading to discomfort and musculoskeletal complaints [17], [24], [32].

Among the bicycle components influencing riding posture, the stem plays an important role in determining the relative position between the handlebar and the rider. Variations in stem geometry directly affect upper-body posture, weight distribution, and riding comfort [15], [20]. Consequently, the ability to adjust stem configuration is essential for accommodating differences in rider anthropometry and achieving a more ergonomic riding position. From an ergonomic perspective, product design should consider the interaction between users, tasks, and equipment to reduce physical workload while improving comfort and usability [21], [25].

Previous studies have demonstrated that modifications to bicycle geometry and riding position influence posture, biomechanical loading, and cycling comfort. Recent systematic reviews have shown that changes in handlebar position and bicycle fitting affect spinal alignment, joint loading, and muscle activation during cycling [15], [24], [35]. Motion capture technology has also been widely adopted to quantify posture changes and evaluate biomechanical responses with high accuracy [24], [27]. Despite these advances, most existing studies have focused primarily on evaluating the effects of bicycle configuration or riding posture, whereas relatively few have integrated user requirements, prototype development, biomechanical analysis, and ergonomic assessment within a single product development framework. As a result, the relationship between user-centred design and objective ergonomic performance remains insufficiently explored.

To address this gap, the present study develops and evaluates an adjustable road bicycle stem using a user-centred design approach. User requirements were first identified through the Voice of Customer (VOC) method and translated into prototype specifications. The prototype was subsequently evaluated by comparing a conventional stem with the proposed adjustable stem using motion-capture-based posture analysis, biomechanical evaluation through trunk moment analysis, and ergonomic assessment based on SNI 9011:2021. By integrating these approaches, this study provides a more comprehensive evaluation framework for adjustable bicycle component design than previous studies that focused on isolated ergonomic or biomechanical parameters.

Accordingly, this study aims to examine the effect of the adjustable stem on riding posture, biomechanical loading, and musculoskeletal complaint risk among road cyclists. The findings are expected to contribute to the development of adjustable bicycle components that better accommodate variations in rider anthropometry while providing practical evidence for integrating ergonomic principles and biomechanical evaluation into bicycle product design.

2. Methods

This study employed a user-centred design approach combined with a comparative experimental design to evaluate the ergonomic and biomechanical performance of an adjustable road bicycle stem prototype. The overall research procedure consisted of five sequential stages: (1) identification of user requirements using the Voice of Customer (VOC) method, (2) prototype design and manufacturing, (3) comparative experimental testing, (4) ergonomic and biomechanical evaluation, and (5) statistical analysis. The complete research workflow is illustrated in **Figure 1**.

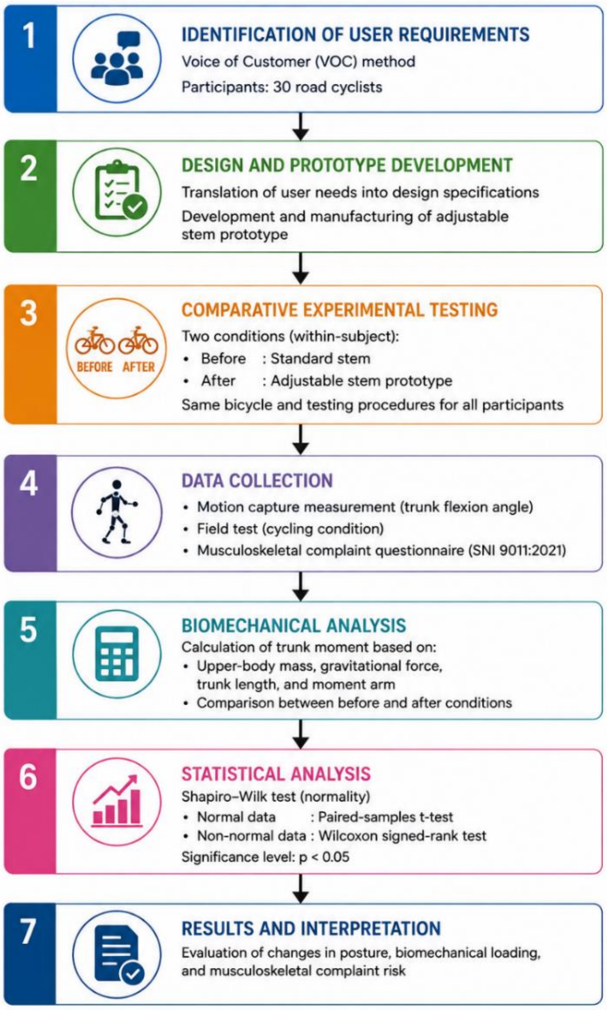

Figure 2. Research Flowchart

The adjustable stem prototype was developed based on user requirements collected from 30 road cyclists through the VOC method. These requirements were translated into design specifications, including handlebar position adjustability, stem angle modification, locking mechanism stability, structural reliability, and riding comfort. Based on these specifications, an adjustable stem prototype was designed and manufactured for experimental evaluation. The completed prototype is presented in **Figure 2**.

Figure 2. Adjustable Stem Prototype

Comparative experimental testing was conducted using the same 30 participants under two testing conditions: the standard stem (before) and the adjustable stem prototype (after). Each participant completed both conditions using the same bicycle configuration and identical testing procedures to ensure measurement consistency. The experiment began with a static test using a bicycle paddock to maintain bicycle stability during posture acquisition, followed by a field test to evaluate riding performance under actual cycling conditions. The static testing setup is shown in **Figure 3**.

Figure 3. Static Test

Body posture was recorded using an Axis Studio motion capture system. Reflective markers were attached to anatomical landmarks to capture body-segment movements, and the recorded data were processed to determine trunk flexion angle. These posture data were subsequently used for biomechanical analysis by calculating trunk moment based on upper-body mass, gravitational force, trunk segment length, and moment arm. The motion capture measurement process is illustrated in **Figure 4**.

Figure 4. Motion Capture Data Collection Using Axis Studio

In addition to biomechanical analysis, ergonomic performance was evaluated using the musculoskeletal complaint assessment instrument based on SNI 9011:2021. The assessment covered the neck, shoulders, elbows, arms, hands, upper back, lower back, and hips to determine changes in musculoskeletal complaint risk between the two testing conditions. The assessment instrument is presented in **Figure 5**.

Biomechanical calculations were performed using human body segment parameters. The first step was to determine upper-body mass based on the proportion of segment mass to the user's body weight. Upper-body mass was calculated using the following equation:

$$m_u = 0.678 \times BW \quad (1)$$

Where:

m_u = upper-body mass (kg)

BW = user's body weight (kg)

0.678 = proportion of upper-body mass based on human body segment parameters

The gravitational force acting on the upper body was then calculated from the relationship between segment mass and gravitational acceleration using the following equation:

$$F = m_u \times g \quad (2)$$

Where:

F = gravitational force acting on the upper body (N)

m_u = upper-body mass (kg)

g = gravitational acceleration (9.81 m/s²)

The next step was to determine trunk-segment length based on the user's body height. Trunk-segment length was used to determine the effective distance of the force from the axis of rotation in the lumbar region. The calculation used the following equation:

$$Ltrunk = 0.30 \times BH \quad (3)$$

Where:

Ltrunk = trunk-segment length (m)

BH = user's body height (m)

0.30 = ratio of trunk-segment length to body height

The distance of the force from the axis of rotation (moment arm) was then calculated based on trunk-segment length and the trunk flexion angle obtained from the motion-capture measurements. The following equation was used:

$$D = Ltrunk \times \cos(\theta) \quad (4)$$

Where:

D = moment-arm distance (m)

Ltrunk = trunk-segment length (m)

θ = trunk flexion angle (°)

The biomechanical trunk moment was then calculated from the relationship between the gravitational force acting on the upper body and the moment-arm distance using the following equation:

$$M = F \times D \quad (5)$$

Where:

M = biomechanical trunk moment (Nm)

F = gravitational force acting on the upper body (N)

D = moment-arm distance (m)The biomechanical trunk moment was

The collected data were analysed using IBM SPSS Statistics. Data normality was first evaluated using the Shapiro–Wilk test because the sample size was fewer than 50 participants. Variables with normal distributions were analysed using the paired-samples t-test, whereas variables that did not satisfy the normality assumption were analysed using the Wilcoxon signed-rank test. A significance level of $p < 0.05$ was used to determine whether differences between the standard stem and adjustable stem conditions were statistically significant.

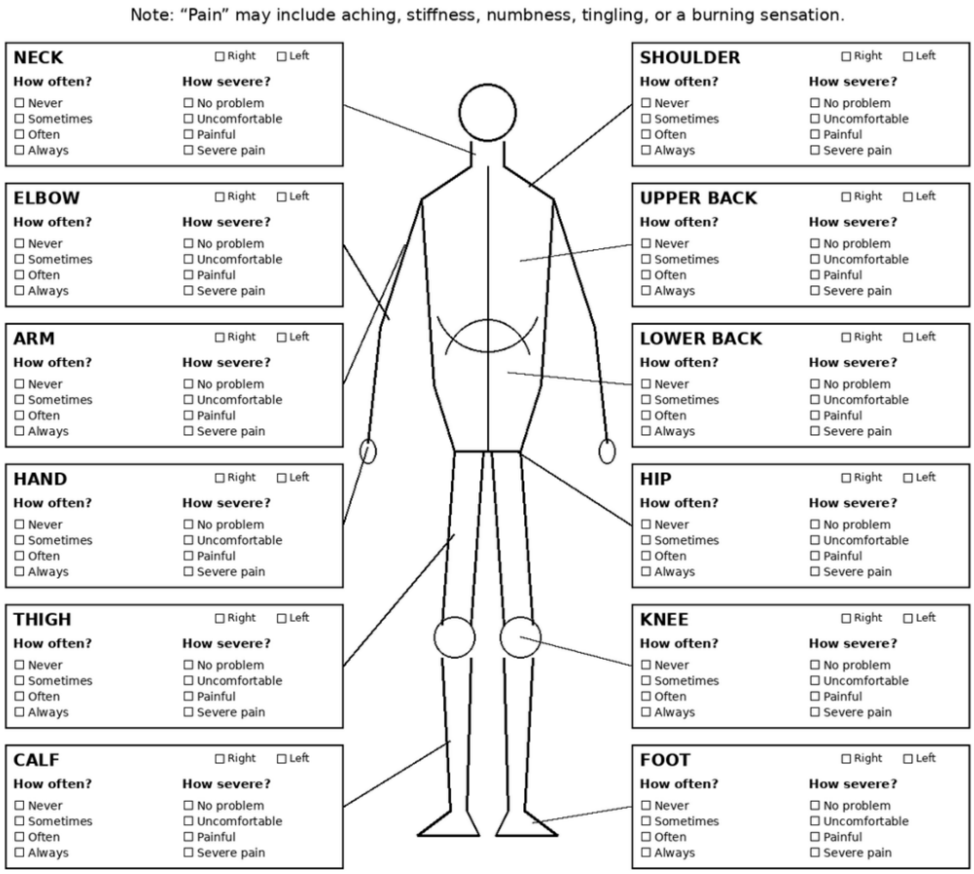

Figure 5. Musculoskeletal Complaint Assessment Instrument Based on SNI 9011:2021

3.Results and Discussion

This section presents the results of the adjustable stem prototype evaluation and discusses its effectiveness based on ergonomic and biomechanical perspectives. The analysis was conducted through several stages, including identification of user requirements, evaluation of postural changes, biomechanical loading analysis, and ergonomic risk assessment. The comparison between the standard stem condition (before) and the adjustable stem prototype condition (after) was performed to determine the impact of the proposed design on riding posture, mechanical loading, and musculoskeletal complaint risk. The findings are discussed to evaluate the extent to which the adjustable stem prototype improves the compatibility between bicycle configuration and user ergonomic requirements.

3.1 Identification of User Needs and Development of the Adjustable Stem Prototype

The development of the adjustable road bicycle stem began with identifying user requirements through the Voice of Customer (VOC) method involving 30 road cyclists. This stage was intended to capture users' experiences, discomfort, and expectations regarding riding posture and handlebar adjustability. The identified requirements formed the basis for translating user needs into engineering specifications and prototype characteristics.

Table 1. User needs identified using the voice of customer (VOC) method

No.	User Need	Identified Problem	Design Response
1	More comfortable riding position	Excessive forward-bent posture	Handlebar-position adjustment
2	Reduced bodily loading	Back and shoulder complaints	Stem-configuration adjustment
3	Adjustable stem	The standard stem has a fixed position	Adjustable mechanism

The VOC analysis revealed that rider discomfort was mainly associated with the limited adjustability of conventional stems, particularly excessive trunk flexion, neck and shoulder discomfort, and the inability to modify riding posture during prolonged cycling. These findings indicate that rider comfort depends not only on bicycle performance but also on the compatibility between bicycle geometry and individual anthropometric characteristics.

Based on these user requirements, an adjustable stem prototype was developed with an angle-adjustment and locking mechanism to provide a more adaptable riding position while maintaining structural stability **Figure 2**. This design follows the principles of user-centred product development, where engineering specifications are derived from user needs to improve comfort and reduce physical workload [8], [9], [10].

The present findings are consistent with previous studies showing that bicycle configuration influences rider posture, biomechanical loading, and cycling comfort [2], [14], [5]. However, unlike earlier studies that mainly evaluated existing bicycle configurations, this study integrates the Voice of Customer (VOC), prototype development, and ergonomic–biomechanical evaluation within a single user-centred design framework. This approach provides an evidence-based foundation for developing adjustable bicycle components that better accommodate variations in rider anthropometry.

3.2 Postural Changes Based on Motion Capture Analysis

Postural changes were evaluated using the Axis Studio motion capture system by comparing trunk flexion angles under two experimental conditions: the standard stem (before) and the adjustable stem prototype (after). Motion capture was selected because it provides objective and accurate measurements of body-segment movements during cycling, allowing quantitative evaluation of changes in riding posture. The posture acquisition process is presented in **Figure 6**. The mean trunk flexion angles obtained under both testing conditions are presented in **Table 2**.

Table 2. Comparison of mean trunk flexion angles before and after

Condition	Mean Trunk Flexion Angle
Before	30.73°
After	52.90°
Change	22.17°

The adjustable stem prototype increased the mean trunk flexion angle by 22.17°, from 30.73° to 52.90°, indicating that handlebar adjustment enabled riders to adopt a posture better suited to their anthropometric characteristics. Riding posture is influenced by the geometric relationship between the saddle, handlebar, and stem, where changes in handlebar position alter trunk orientation, upper-body weight distribution, and spinal loading [15], [20].

These findings agree with previous studies showing that bicycle configuration significantly affects rider posture and biomechanical responses. Husband et al. [15] reported that handlebar adjustment influences cycling biomechanics, while Patti et al. [20] and Muyor et al. [20] demonstrated that changes in bicycle geometry modify spinal alignment and trunk posture. Unlike these studies, the present research integrates the Voice of Customer (VOC), prototype development, and motion capture analysis to evaluate an adjustable stem through a user-centred design approach.

From an ergonomic perspective, the improved riding posture may reduce excessive loading on the neck, shoulders, and upper back, thereby enhancing rider comfort during prolonged cycling [17], [21], [25]. Although trunk flexion angle alone cannot fully represent ergonomic improvement, its concurrent reduction in biomechanical loading and musculoskeletal complaint risk suggests that the proposed adjustable stem provides a more ergonomic riding configuration. These findings provide the basis for the subsequent biomechanical loading analysis.

3.3 Biomechanical Loading Analysis

Changes in riding posture obtained from the motion capture analysis were subsequently used to evaluate biomechanical loading by calculating the trunk moment under both experimental conditions. Trunk moment represents the mechanical load acting on the upper body and is influenced by body posture, gravitational force, and the horizontal distance between the upper-body centre of mass and the lumbar axis of rotation. Consequently, changes in trunk posture resulting from stem adjustment are expected to alter the magnitude of the trunk moment experienced during cycling. The comparison of trunk moment values before and after using the adjustable stem prototype is presented in **Table 3**.

As shown in **Table 3**, the adjustable stem prototype reduced the mean trunk moment from 193.94 Nm to 136.13 Nm, representing a reduction of 57.83 Nm. This finding indicates that modifying the stem configuration substantially decreased the mechanical loading acting on the rider's upper body. The reduction occurred because the adjustable stem altered the rider's posture, thereby shortening the effective moment arm between the upper-body centre of mass and the lumbar spine. As the moment arm decreased, the external moment acting on the trunk was also reduced, resulting in lower biomechanical loading.

Table 3. Comparison of biomechanical moment values before and after

Condition	Moment Value
Before	193.94 Nm
After	136.13 Nm
Change	-57.83 Nm

To determine whether the observed reduction was statistically significant, a paired-samples t-test was performed because trunk moment values satisfied the normality assumption and were obtained from the same participants under two experimental conditions.

Table 4. Paired-Samples t-test results for changes in biomechanical moment

Paired Samples Test									
		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Before - After	57.833	22.338	4.078	49.492	66.174	14.181	29	.000

The paired-samples t-test showed a significant reduction in trunk moment between the two testing conditions ($t = 14.181$, $p < 0.001$), indicating that the observed improvement resulted from the adjustable stem prototype rather than random variation. From a biomechanical perspective, reducing the distance between the body's centre of mass and the lumbar spine decreases trunk loading and muscular effort required to maintain cycling posture [21], [37]. Accordingly, the reduction in trunk moment suggests that the adjustable stem improved load distribution by optimising the rider–bicycle geometry.

These findings are consistent with previous studies reporting that bicycle configuration influences biomechanical loading and riding posture. Husband et al. [15] demonstrated that handlebar adjustment affects upper-body loading, while Patti et al. [24] and Rodríguez Samaca et al. [28] reported that bicycle fitting and handlebar reach significantly influence spinal alignment and cycling biomechanics.

Unlike previous studies, the present research integrates the Voice of Customer (VOC), prototype development, motion capture, and biomechanical analysis within a user-centred design framework.

Lower trunk loading may reduce muscular fatigue and the risk of musculoskeletal complaints in the neck, shoulders, and lower back during prolonged cycling [17], [31], [32]. Although the evaluation was conducted under controlled conditions, the results provide biomechanical evidence that the proposed adjustable stem offers a more ergonomic riding configuration and establish the basis for the subsequent ergonomic risk assessment.

3.4 Ergonomic-Risk Evaluation

The ergonomic performance of the adjustable stem prototype was evaluated using the musculoskeletal complaint assessment instrument specified in **SNI 9011:2021**. The assessment compared discomfort scores before and after using the adjustable stem across eight body regions that are commonly exposed to loading during road cycling, including the neck, shoulders, elbows, arms, hands, upper back, lower back, and hips.

Table 5. Comparison of ergonomic risk based on SNI 9011:2021

Body Region	Before	After
Neck	10.37	3.47
Shoulder	10.17	3.53
Elbow	5.73	2.73
Arm	9.57	2.73
Hand	6.97	3.07
Upper Back	11.33	3.07
Lower Back	10.50	3.53
Hip	5.40	2.93

As presented in **Table 5**, ergonomic risk scores decreased across all evaluated body regions following the use of the adjustable stem prototype. The greatest improvements were observed in the upper back, lower back, shoulders, and neck, which are the body regions most affected by prolonged forward-leaning cycling posture. These results indicate that modifying handlebar position through the adjustable stem reduced postural stress and improved load distribution throughout the upper body.

To evaluate the statistical significance of these changes, a Wilcoxon signed-rank test was performed because the ergonomic assessment data did not satisfy the assumption of normality. The Wilcoxon signed-rank test showed significant reductions in ergonomic risk scores across all assessed body regions ($p < 0.001$), indicating that the improvements associated with the adjustable stem were consistent among participants. Prolonged cycling in a fixed forward-leaning posture is known to increase muscular loading in the neck, shoulders, and lumbar region, contributing to fatigue and musculoskeletal discomfort [17], [31], [32]. By allowing handlebar adjustment according to rider anthropometry, the proposed stem reduced postural loading and improved force distribution, consistent with ergonomic principles that emphasise adapting products to users [21], [25].

Table 6. Wilcoxon signed-rank test results for ergonomic risk before and after

Test Statistics[a]								
After - Before	Neck	Shoulder	Elbow	Arm	Hand	Upper Back	Lower Back	Hip
Z	-4.814[b]	-4.818[b]	-4.945[b]	-4.811[b]	-4.875[b]	-4.824[b]	-4.810[b]	-4.919[b]
Asymp. Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000

These findings agree with previous studies showing that improved bicycle fitting enhances rider comfort and reduces biomechanical stress. Husband et al. [15], Patti et al. [24], and Vicari et al. [35] similarly reported that optimizing bicycle configuration improves spinal posture, cycling comfort, and musculoskeletal outcomes. Although the evaluation was conducted under controlled conditions, the results suggest that the adjustable stem provides ergonomic benefits and warrant further validation under long-term and real-road cycling conditions.

3.5 Overall Discussion and Research Implications

The findings demonstrate that integrating a user-centred design approach with ergonomic and biomechanical evaluation provides an effective framework for developing adjustable bicycle components. The Voice of Customer (VOC) analysis guided the development of an adjustable stem prototype that improved riding posture, reduced trunk moment, and lowered musculoskeletal complaint risk, indicating enhanced compatibility between bicycle configuration and rider anthropometry.

These results are consistent with previous studies highlighting the influence of bicycle geometry and rider positioning on posture, comfort, and biomechanical loading [15], [20], [24]. Unlike earlier studies that primarily evaluated existing bicycle configurations, the present research integrates user requirement identification, prototype development, motion capture analysis, biomechanical modelling, and ergonomic assessment within a single evaluation framework. This integrated approach represents the main contribution of the study by providing objective evidence that user-centred product design can improve ergonomic performance.

From a practical perspective, the proposed adjustable stem offers a flexible solution for accommodating anthropometric variability while potentially improving rider comfort and reducing upper-body loading. However, the findings should be interpreted within the study limitations, including the relatively small sample size, controlled testing environment, and short-term evaluation. Future research should involve more diverse participants, longer riding durations, and real-road conditions to further validate the long-term ergonomic and biomechanical benefits of adjustable bicycle components.

4. Conclusion

This study developed and evaluated an adjustable road bicycle stem prototype using a user-centred design approach integrating the Voice of Customer (VOC), motion capture, biomechanical analysis, and ergonomic assessment. The prototype improved rider posture by increasing the mean trunk flexion angle by 22.17°, reduced the mean trunk moment by 57.83 Nm, and lowered musculoskeletal complaint risk based on the SNI 9011:2021 assessment. These findings suggest that an adjustable stem may improve the compatibility between bicycle configuration and rider anthropometry under the experimental conditions of this study.

The primary contribution of this research is the integration of user requirement identification with ergonomic and biomechanical evaluation within a single product development framework, providing an evidence-based approach for designing adjustable bicycle components.

However, the findings should be interpreted within the study limitations, including the relatively small sample size, controlled testing environment, and evaluation of a single prototype. Future studies should involve more diverse participants, longer riding durations, and real-road conditions to further validate the long-term ergonomic and biomechanical benefits of adjustable bicycle components.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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