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ERGONOMIC EVALUATION OF A FOLDING BIKE DESIGN USING VIRTUAL ENVIRONMENT MODELLING

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ABSTRACT

The purpose of this paper is to evaluate the ergonomics aspects of the first prototype of a folding bike designed by the Department of Mechanical Engineering, University of Indonesia (DME UI) in a virtual environment. Posture Evaluation Index (PEI) is used as an analysis approach that integrates the results of three methods: Low Back Analysis (LBA), Ovako Working Posture Analysis System (OWAS), and Rapid Upper Limb Assessment (RULA). The objective is to determine the optimal design configuration of a folding bicycle based from an ergonomics perspective. For male and female riders, the optimal configuration is obtained when the height of the handlebar is 32 cm and the height of the saddle is 83 cm. This study proved that a virtual environment could strengthen the ergonomics evaluation, especially in posture condition exploration.

Keywords: Ergonomics; Folding bike; Posture Evaluation Index; Virtual environment

1. INTRODUCTION

In many countries, the bicycle has been introduced as part of the urban transportation system to extend the accessibility of public transportation systems to final destinations. Public bicycle systems have been promoted in urban cities around the world such as Paris, Barcelona, Berlin, Montreal, Salt Lake City (Lin & Yang, 2010). As a developing country, Indonesia has not considered the bicycle as main component of its transportation system. Usage of bicycles can help reduce air pollution produced by fuel combustions and has many advantages compared to other transportation mode (Guitink, et al., 1994). These facts have caused some communities to promote “Bike to Work” movements.

Department of Mechanical Engineering (DME), Faculty of Engineering, Universitas Indonesia, also considered that there are many requirements for bicycle development in Indonesia, so this institute tried to take a role. DME designed the first prototype of a folding bicycle and manufactured it in cooperation with a local manufacturer. This folding bike is expected be widely used in the future. However, the ergonomic aspects had not been major consideration in the initial design of DME’s folding bike.

Ergonomics is the study of the interaction between people and machines/tools and the factors that affect the interaction. Its purpose is to improve the performance of systems by improving human-machine/tools interaction (Bridger, 2003). Ergonomics research has been proven to provide benefits in improving human conformance and effectiveness when using tools, such as the foot pedal used by surgeons (van Veelen, 2003).

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Ergonomics has also proven useful in evaluating the structural anthropometric dimensions of adult wheelchair users (Paquet, 2004), providing the results of a field study of assembly jobs in the automotive industry (Landau, 2008), and evaluating back-mounted packs/devices worn by workers while working in non-neutral trunk postures (Southard, 2007). Specifically, published studies regarding the ergonomic aspect of the bicycle and its related parts, including handlebar design (Arbogast et al., 2001), seat design (Bressel et al., 2009), and hand grip position (Duc et al., 2008; Bressel & Cronin, 2005). Donkers et al. (1993) and Laios and Giannatsis (2010), conducted an assessment and redesign of a child's bicycle on the basis of anthropometric data. As Laois and Giannatsis (2010) noted, proper bicycle fit is very important for cycling performance, efficiency, comfort, and injury prevention. Lack of fit between the dimensions of the bicycle and the human rider could result in an accident (Donkers et al., 1993).

One of the newest approaches in ergonomic analysis is the virtual environment (VE). VE is an artificial environment created on a computer and used in real time (Kalawsky, 1993). The application of VE has been used widely to support the ergonomics evaluation, including researches conducted by Di Gironimo et al. (2004); Caputo et al. (2006); Li et al. (2006); Lämkull et al. (2007); Lämkull et al. (2009); Cimino, et al. (2009); and Laois and Giannatsis (2010).

In the long run, lack of ergonomics research in the design of DME's folding bike may have been the cause of discomfortness to riders. In this study, the DME's folding bike was analyzed using an ergonomics study in a virtual environment. Posture Evaluation Index (PEI) was used to measure the level of bikers' conformance. This approach combines the analysis results from three methods: Low Back Analysis (LBA), Ovako Working Posture Analysis System (OWAS), and Rapid Upper Limb Assessment (RULA). The objective of this research is to determine the optimal design configuration of a folding bicycle based on an ergonomics perspective.

2. METHODOLOGY

The first step of this research was to measure the object's specifications in the real world that would be used in virtual modelling. The objects are DME's folding bike (Figure 1), the slope of UI's bicycle track, and anthropometry data from UI students.

The next step was creating the model of the observed objects and importing them to the virtual environment in Jack 6.0 software. Jack 6.0 is an ergonomics and human factors product, enabling users to biomechanically position accurate digital humans of various sizes in virtual environments, assign them tasks and analyze their performance (Di Gironimo et al., 2001). The mannequin model was built by converting the anthropometry data to become a human model in Jack 6.0. Real conditions felt by real human were programmed into the model's virtual environment. The mannequin was positioned in a posture similar to the real working posture condition (UGS Tecnomatix, 2005). The position of the mannequin was influenced by two variables: the height of the handlebar and the height of the saddle. Pedal height was excluded from the manipulation process because its position cannot be adjusted in the DME's actual folding bike.

DME's drawing of the folding bike's was created in SolidWorks 2007 software and then imported to Jack 6.0. The configuration of the model was determined by the height of the handlebar and the height of the saddle. Table 1 shows the configuration of DME's folding bike models. The height of the handlebar was measured from the central stern of bicycle to the handle bar. The height of the saddle was measured from the saddle to the ground. The first configuration is the current combination of DME's folding bike specification, while the others are proposed designs.

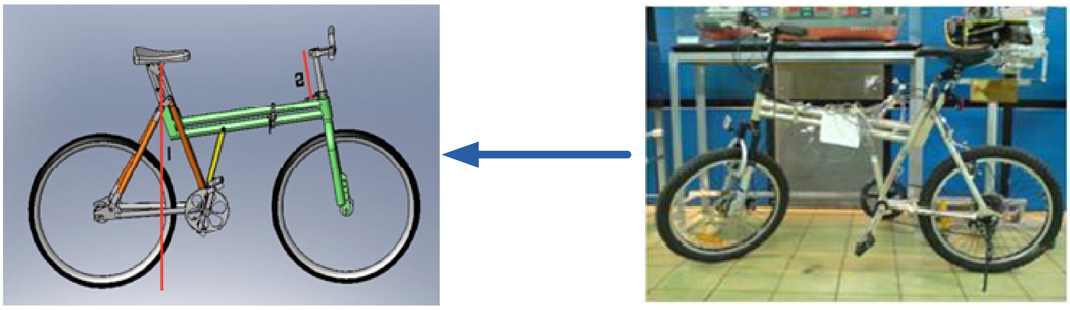

Figure 1 DME's folding bike model

Table 1 Configuration of DME's folding bike models

Configuration	Height of Handlebar (from central stern of bicycle)	Height of Saddle (from Ground)	Info
1	12 cm	83 cm	Actual
2	12 cm	87 cm	Proposed
3	12 cm	91 cm	Proposed
4	22 cm	83 cm	Proposed
5	22 cm	87 cm	Proposed
6	22 cm	91 cm	Proposed
7	32 cm	83 cm	Proposed
8	32 cm	87 cm	Proposed
9	32 cm	91 cm	Proposed

The research phase was continued by manipulating and simulating the riding bicycle activity. The steps of these activities can be seen in Figure 2.

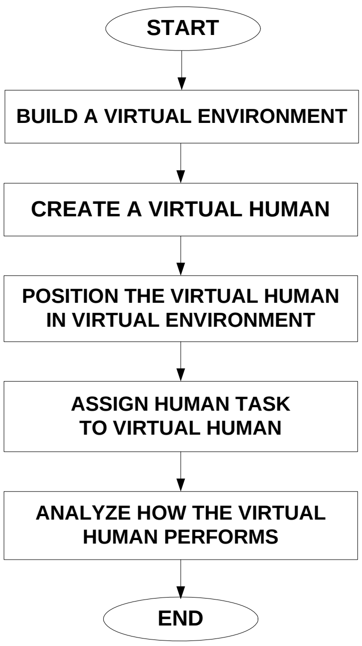

Figure 2 Simulation and manipulation steps

The analysis of impact by the virtual human was conducted using four methods in the Jack Analysis Toolkit (TAT): Static Strength Prediction (SSP), Low Back Analysis (LBA), Ovako Working Posture Analysis System (OWAS), and Rapid Upper Limb Assessment (RULA).

These four analyses were conducted only in virtual environment, not in the real world, to make the folding bike model interact with the so-called ”representative” mannequin generated by Jack 6.0 from anthropometry data. As supported by Caputo et al. (2006), usage of the virtual environment in this research can also eliminate some difficulties faced in “real world” ergonomics research which has been regarded as reactive, time-consuming, incomplete, sporadic, and difficult. SSP, LBA, OWAS, and RULA can be applied to cycling activities, because these approaches were are concerned with posture condition when performing a task, as supported by McAtamney and Corlett (1993). Cycling activities create a cycling posture that can be evaluated in Jack 6.0 software.

SSP was used to evaluate the percentage of the overall population that is able to perform the assigned activity. If the percentage is equal to or greater than 90%, then the activity can be analyzed with LBA, OWAS, and RULA (Caputo et al., 2006).

The research continued with an analysis of the riding bicycle activity using LBA, OWAS, and RULA. Then the results of these methods were integrated using the Posture Evaluation Index (PEI). PEI score is the sum of non-dimensional variables I1, I2, and I3. I1 is the LBA value that is normalized with the NIOSH limit for compression strength (3400 N). I2 and I3 are respectively equal to the OWAS index normalized with its critical value (“4”) and the RULA index normalized with its critical value (“7”) (Di Gironimo et al., 2004). The calculation of PEI score would make the analysis become easier because it simplified scoring comparison among all of the configurations.

$$PEI = I_1 + I_2 + mr.I_3 \tag{1}$$

where:
I_1= LBA/3400 N, I_2= OWAS/4, I_3=RULA/7, and mr is *amplification factor* equal to 1.42.

The optimal configuration, that will give the most convenient condition for the rider is the configuration with the lowest PEI score (Caputo et al., 2006).

3. RESULTS

The slope of the track was measured by a theodolite, owned by the Department of Civil Engineering, UI. Measurement results are shown in Table 2. Then, the anthropometry data was measured which included 30 UI male riders and 30 UI female riders. A normality test was conducted to make sure that the data distributed normally. Bridger (2003) noted that healthy anthropometry data follows a normal distribution. The anthropometry data is shown in Table 3.

After the necessary data obtained, the virtual environment was created by importing all objects to Jack 6.0. The objects were positioned in the environment to simulate conditions in the real world. After that, the virtual human was given the task of riding a bicycle on two types of track: flat track with 0% road slope and ascent track using the highest road slope of the longest track in UI (7,83% slope). The other place with higher road slope was excluded because the length of track was too short to influenced the workload received by riding posture.

After all of configuration were simulated, the SSP was conducted. Since all the configurations were more or equal than 90% in SSP score, then, the activity can be analyzed with LBA, OWAS, and RULA.

Finally, the PEI score was calculated. The results from LBA, OWAS, RULA, and PEI calculation are shown in Table 4. The lowest PEI score is represented by configuration and the highest PEI score is represented by configuration 3.

Table 2 The Road Slope of UI's Track

Place	Slope Percentages
Pusgiwa	3.05
Water Tower	7.83
Balairung Park	2.82
Balairung (UI Lake)	8.93
Front of UI Economy Faculty	2.04
	2.06
First UI Gate	7.13
Second UI Gate	11.5
	6.06
Front of UI Stopping Place	9.14
	9.3
Front of Mang Engking Restaurant	3.8

Table 3a Anthropometry data for male riders

Dimension of Male Bikers	Percentile		
	5th	50th	95th
Body Weight (kg)	51.8	51.5	65.95
Body Height (cm)	163.9	157.75	164.775
Arm Length (cm)	74.68	71	74.55
Elbow-Fingertips (cm)	45	43	45.55
Shoulder-Elbow (cm)	34	32	35
Hand Breadth (cm)	9	9	10
Hand Length (cm)	17.75	17	18.365
Buttock-Knee (cm)	57	54	60
Hip Breadth (cm)	31.45	35	37.55
Foot Breadth (cm)	8.5	9	10.275
Foot Length (cm)	24	23	25
Ankle Height (cm)	7	6.5	7.5
Sit Knee Height (cm)	48	48.25	52

Table 3b Anthropometry data for female riders

Dimension of Female Bikers	Percentile		
	5th	50th	95th
Body Weight (kg)	42	51.5	65.95
Body Height (cm)	150	157.75	164.775
Arm Length (cm)	65.9	71	74.55
Elbow-Fingertips (cm)	39.45	43	45.55
Shoulder-Elbow (cm)	30.45	32	35
Hand Breadth (cm)	8.5	9	10
Hand Length (cm)	15.725	17	18.365
Buttock-Knee (cm)	51.225	54	60
Hip Breadth (cm)	30.725	35	37.55
Foot Breadth (cm)	8.39	9	10.275
Foot Length (cm)	21.27	23	25
Ankle Height (cm)	5.225	6.5	7.5
Sit Knee Height (cm)	44.45	48.25	52

4. DISCUSSION

The first step of analysis was SSP analysis. All of the configurations had SSP score equal to or greater than 90%. This percentage indicated that the majority of the riders measured could perform the bicycling activity. Then, LBA confirmed the same trend for male and female riders; the LBA score increased when the height of the saddle was raised for the same handlebar height. Another trend was that LBA score declined when the height of the handlebar was raised. The trends may be explained by the position of the mannequin's back. When the back was crooked with a higher degree, the LBA score continued to increase. In general, the LBA score for female riders were lower than the score for male riders. This condition is natural, because the dimension of a female rider's back and the female's body weight are lower than the dimensions for male riders.

The female body experiences a lower compression force when riding a bicycle. OWAS showed same trend for all configuration, with OWAS score of 3. This score indicates that the riders' posture will cause harmful levels of stress on the musculoskeletal system unless immediate corrective measures are taken. RULA results indicated that female riders susceptible to upper limb injuries than male riders. This condition can be explained by the arm length dimension of female riders. The female body has a shorter arm length than the male, so the female must bend their bodies to adjust with riding position. When the body is crooked at a higher degree, then the RULA score increases.

Table 4 LBA, OWAS, RULA, and PEI calculation results

Configu-ration of Male Bikers	LBA (newton)		OWAS	RULA	PEI SCORE		Configu-ration of Female Bikers	LBA (newton)		OWAS	RULA	PEI	
	Flat	Ascent			Flat	Ascent		Flat	Ascent			Flat	Ascent
1	1552	1520	3	6	2.424	2.414	**1**	1141	1104	3	6	2.303	2.292
2	1606	1585	3	6	2.439	2.433	**2**	1316	1309	3	6	2.354	2.352
3	1772	1750	3	6	**2.488**	**2.482**	**3**	1325	1335	3	7	**2.560**	**2.563**
4	1191	1171	3	3	1.709	1.703	**4**	1110	1098	3	6	2.294	2.290
5	1441	1370	3	6	2.391	2.370	**5**	1104	1111	3	6	2.292	2.294
6	1529	1528	3	6	2.417	2.417	**6**	1187	1182	3	6	2.316	2.315
7	1183	1008	3	3	**1.707**	**1.655**	**7**	890	857	3	5	**2.026**	**2.016**
8	1193	1125	3	4	1.912	1.892	**8**	908	919	3	6	2.234	2.237
9	1209	1291	3	4	1.917	1.941	**9**	938	942	3	6	2.243	2.244

The comparison of PEI score between male and female riders (Figure 3) indicated several things. First, the current condition of DME's folding bike (from configuration 1) is more comfortable for female riders than for males. But, in general, from all configurations, it can be concluded that adjustment to the handlebar and saddle can make male riders feel as comfortable as females. Second, the optimal configuration for male and female riders is configuration 7, as indicated by the lowest PEI score. This configuration is gained when the height of the handlebar is 32 cm and the height of the saddle is 83 cm. This means that configuration 7 should provide the most comfortable conditions for the riders. This finding can help DME improve its folding bike design, before the next generation of DME's folding bike is manufactured. Results of this study conform to that of Caputo et al. (2001) who indicated that the virtual environment could evaluate designs based on ergonomic factors before the physical prototypes are built.

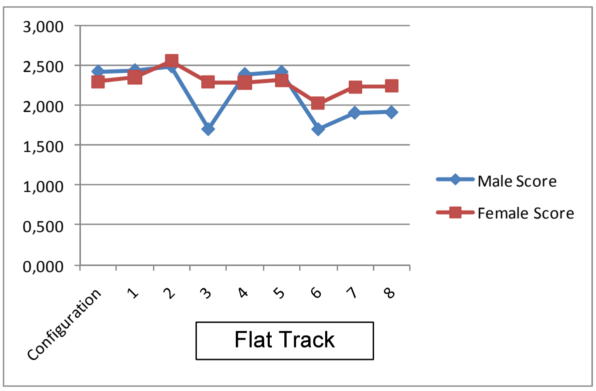

Figure 3a PEI Score for male riders

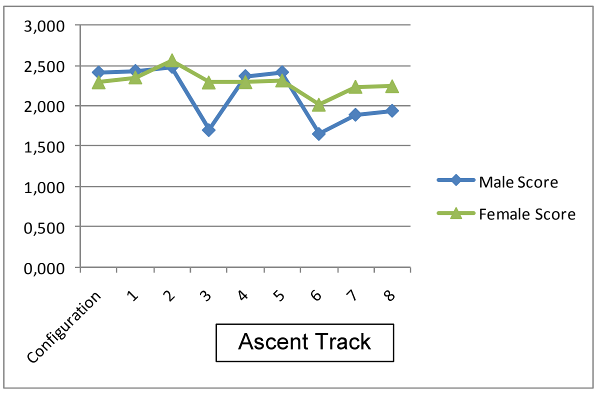

Figure 3b PEI Score for female riders

5. CONCLUSION

This research evaluates the ergonomics aspects of the first prototype of DME's folding bike. The Posture Evaluation Index, that combined LBA, OWAS, and RULA, was used as an approach to analyze the conformance of the riders when riding. Results indicated:

1. All of configuration may harm the musculoskeletal systems of the riders.
2. The current condition of DME's folding bike are more comfortable for female riders than male.
3. Adjustment to the handlebar and the saddle can make male riders feel comfortable as females.
4. Optimal configurations are obtained when the height of the handlebar is raised 20 cm from the current height and the height of saddle remains the same. This finding can help DME improve its folding bike, because the current design may harm its riders.
5. This study proved that a virtual environment can strengthen the ergonomics evaluation, especially in posture condition exploration.

6. ACKNOWLEDGEMENT

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