Muscle fatigue based evaluation of bicycle design

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ABSTRACT

Bicycling posture leads to considerable discomfort and a variety of chronic injuries. This necessitates a proper bicycle design to avoid injuries and thereby enhance rider comfort. The objective of this study was to investigate the muscle activity during cycling on three different bicycle designs, i.e., rigid frame (RF), suspension (SU) and sports (SP) using surface electromyography (sEMG). Twelve male volunteers participated in this study. sEMG signals were acquired bilaterally from extensor carpi radialis (ECR), trapezius medial (TM), latissimus dorsi medial (LDM) and erector spinae (ES), during 30 min of cycling on each bicycle and after cycling. Time domain (RMS) and frequency domain (MPF) parameters were extracted from acquired sEMG signals. From the sEMG study, it was found that the fatigue in right LDM and ES were significantly ($p < 0.05$) higher in SP bicycle. This was corroborated by a psychophysical assessment based on RGB pain scale. The study also showed that there was a significantly lesser fatigue with the SU bicycle than the RF and SP bicycles.

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1. Introduction

Bicycle is a popular and economical mode of human-powered transportation. This also enables it to be used as effective equipment towards fitness and rehabilitation (Balasubramanian and Jayaraman, 2009). However, bicycling demands one to bend forward while pedaling; this prolonged forward flexion posture may increase the risk of chronic conditions such as musculoskeletal disorders (MSD), compression neuropathies, and so on. Hence, proper bicycle design is necessary to reduce MSD and enhance comfort for riders (Laios and Giannatsis, 2010; Mellion, 1994; De Vey Mestdagh, 1998).

Cyclists adopt a round-back or flat-back posture to reach the handlebars by flexing their pelvis and spine (Burke, 1996; Usabiaga et al., 1997). Cyclists who maintain a prolonged aerodynamic posture experience pronounced stress on their shoulder, neck and low back pain (Mellion, 1994; Burnett et al., 2004). For example, the working schedule for a bicycle messenger is normally around 40 h per week. This prolonged bicycling demands a very high physical capacity with high energy expenditure which often exceeds the recommended level (mean oxygen uptake ($\text{VO}_2$) during an 8 h working day should not exceed 30% of the maximum capacity of oxygen uptake) and subsequently develops fatigue (Bernmark et al., 2006). An individual’s control over the bicycle depends on his capability to balance the upper body and the strength of his core muscles. When less energy is spent on balancing the upper body, an individual can spend more energy on powering the bicycle (using the lower body). This is the main reason why cycling training centers are considered important; to improve the efficiency and health of the upper body, especially because of the strength they provide to the lower back muscles which is one of the primary posture section of a cyclist’s body (Li and Caldwell, 1998).

Muscle fatigue is an important feature affecting cycling performance. It has been reported that muscle fatigue would alter the cycling motion and muscle activation pattern (So et al., 2005). Houtz and Fisher (1959) investigated muscle’s activity patterns on a stationary bicycle using surface electromyography (sEMG). During a fatigu ing contraction, the sEMG amplitude has been established to increase in submaximal contractions (De Luca, 1984; Krogh-Lund and Jorgensen, 1992; Van Dieen et al., 1993; Ferguson et al., 2012). At the same time, there is an increase in the lower frequency components of the sEMG spectrum during sustained contractions. These frequency changes have been used as an indicator of muscle fatigue (De Luca, 1984, 1993). During prolonged bicycling, muscle fatigue results from metabolic changes in the recruited muscle fibers, causing a decrease in the force-generating capacity of the skeletal muscle (Gibson et al., 2001).

Endurance cycling requires prolonged flexed posture, which appears to be one of the main reasons for lower limb and lower body problems (Callaghan, 2005; Hausswirth et al., 2010). Since cycling relies almost entirely on the lower body for propulsion across the terrain in a seated position, numerous cycling studies...

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have examined mostly the lower extremity muscles (Brown et al., 1996; Gregor et al., 1982). This has not been the case for the effects of upper body orientation on neuromuscular control during cycling (Chapman et al., 2008). Balasubramanian and Jayaraman (2009) investigated sEMG based muscle activity analysis on upper body muscle-groups for aerobic cyclists. The results suggested that there is higher muscle fatigue in low back pain group when compared to their cohorts. Researchers have reported that the low back pain occurs due to cyclist’s posture on the bicycle (De Vey Mestdagh, 1998). Hence, an appropriate bicycle design is very important to avoid health problems and discomforts associated with cycling (Baker, 2000).

The effective progress of studies on cycling over several decades has led to various bicycle designs like sport bicycles, road bicycles and mountain bicycles (Wilson, 2004). Bicycles are designed to meet specific needs that are usually associated with cycling efficiency, safety and comfort. Each bicycle designer designs different frame sizes and dimensions for seat and handlebar, reflecting the qualities of their brands and satisfying the demands of their users. Some cyclists who suffer from back-pain modify their bicycle design with extra-high handlebars so that they can sit upright, with their backs straight. High handlebars decrease the load on the lower cervical spine and reduce the risk of prolonged neck extension (Kolehmainen et al., 1989).

Majority of the bicycle design studies focus on race cycling and the relationship between posture and prevention of injuries caused during long periods of cycling (Berry et al., 2000). There have been fewer investigations on the relationship between posture and the cyclist’s comfort factor and bicycle design (Laios and Giannatsis, 2010; Christiaans and Bremner, 1998). Hence, there is a need for a comparison of the physiological responses of cyclists riding different bicycle categories. We considered three categories of bicycle design, namely:

1. Rigid frame bicycle (RF): It has a frame with a rigid fork, fixed rear and no suspension.
2. Suspension bicycle (SU): It uses linkages to attach the rear triangle to the rear shock for a progressive spring rate.
3. Sports bicycle (SP): It has a (racing) drop handlebar, narrow tyres and no suspension.

The main objective of the study was to evaluate bicycle design using sEMG, by examining whether differences in muscle activity existed in cyclists whilst performing a continuous ride on RF, SU and SP bicycle designs.

2. Methods and materials

2.1. Participants

Twelve male volunteers participated in this study after they were briefed extensively on the scope and objectives of this study. Five participants were more familiar with racing handlebars, and remaining seven with standard handlebar configurations. Participants had the following physical characteristics (mean ± SD): body mass = 63.5 ± 5.4 kg, body height = 1.74 ± 0.04 m, age = 23.2 ± 3.3 yrs. These volunteers were from the Rehabilitation Bioengineering Group laboratory at IIT Madras, India. They signed the informed consent that conformed to the ethical guidelines of IIT Madras.

2.2. Experimental design and protocols

All participants were fully aware of the experiments before participating in it. A within-participant design was utilized, with each participant riding all three bicycles as shown in Fig. 1. The bicycle dimensions of RF and SU bicycles were the same. They were having a wheel diameter of 0.60 m, seat height of 0.85 m, handlebar height of 0.95 m and seat-handlebar distance of 0.60 m. SP bicycle however had a wheel diameter of 0.70 m, seat height of 0.95 m.
handlebar height of 0.82 m and seat-handlebar distance was 0.85 m.

The order in which the participants rode the bicycles was randomized. They were instructed to sit and maintain a comfortable posture and a constant speed throughout the testing session. Test track was chosen within the Institute premises, which has a near flat terrain at an altitude of about 10–20 m above mean sea level. This black topped terrain had non-periodic speed bumps and a low traffic density. Time bound for testing duration (30 min total) allowed the participants to cover a distance of 8 km. The study was carried out for each participant on consecutive days. Each participant completed maximal voluntary contraction (MVC) test before and after riding each time. Changes in muscle activity during on-road cycling were quantified each time a participant rode a bicycle.

2.3. sEMG data acquisition and analysis

The hands, arms, shoulders and back form a muscular sling, which travels back and forth in supporting the upper body and pelvis during the pedaling motion (Schmidt, 1994; Balasubramanian and Jayaraman, 2009). Hence, sEMG activity from those muscle groups (extensor carpi radialis (ECR), trapezius medial (TM), latissimus dorsi medial (LDM) and erector spinae (ES)) was bilaterally recorded as shown in Fig. 2 sEMG signals were recorded using Myomonitor® Wireless EMG Systems (Delsys Inc., Chicago) with single differential electrode configuration. The reference electrode was placed on wrist bone (electrically neutral tissue). The skin was shaved, abraded and cleaned with ethanol before placing the electrodes to get better contact between the skin and the electrodes and also to reduce skin impedance.

Prior to and after the experiment, participants were asked to exert MVC for each muscle group chosen. For measurement of voluntary activation of muscle groups during maximal contraction test, participants were asked to lift the weights from the ground as fast as possible (Fig. 3). All MVCs were collected for 5 s and three trials were performed. The highest generated contraction from each muscle group during the three trials was averaged to be the MVC. Then, they were instructed to start the on-road cycling. sEMG signals were recorded to determine the activity levels of the muscle groups during riding.

All raw sEMG signals were digitized with a sampling rate of 1000 Hz and filtered using band pass filter (20–450 Hz) and band stop filter (47–51 Hz). An ensemble mean of sEMG amplitude was calculated for each muscle group. To reduce within-participant variability, the filtered signal was amplitude normalized to the calculated mean value. The normalized signal was segmented into 10 s each for interval of 1 min and then stored for subsequent analysis. The sEMG data were extracted and processed in MATLAB™ (Mathworks™, Inc., USA).

2.3.1. Time domain analysis

sEMG behaviour during fatigue is associated with increase in the root mean square (RMS) of the time signal (Krogh-Lund and Jorgensen, 1993; Balasubramanian and Jayaraman, 2009). Hence RMS of sEMG signal is one of the most reliable parameters in the time domain analysis (Basmajian and De Luca, 1985). Slope of RMS with respect to time is an indicator of neuromuscular efficiency; thus weaker muscles are described by positive slopes which indicate that the muscles are able to generate less force to maintain the level of contraction then to actual task (Gaudreault et al., 2005). In this study, an RMS change during MVC was computed as the difference in RMS value before and after riding. It was expressed in terms of percentage deviation as depicted in equation (1):

\[
\text{% Deviation in RMS} = \frac{\text{RMS}_{\text{after}} - \text{RMS}_{\text{before}}}{\text{RMS}_{\text{after}}} \times 100
\]

(1)

The changes in RMS during on-road cycling were calculated and analysed using linear regression and the corresponding slopes were determined.

2.3.2. Frequency domain analysis

Method for evaluating the frequency domain power spectrum of sEMG signal to muscle fatigue has been well-studied (De Luca, 1984). In this study, power spectrum was determined using a spectral hamming window with a length of 128 samples for each segment. Mean power frequency (MPF) was estimated from the power spectrum. The MPF changes during MVC test were computed using equation (2). The slope of MPF versus time (fatigue rate), was also calculated and analysed by linear regression. The negative slope of the regression line would indicate fatigue rate (Gaudreault et al., 2005). Hence RMS and MPF of the sEMG signal were used as the fatigue indicator parameters in this study.

\[
\text{% Deviation in MPF} = \frac{\text{MPF}_{\text{after}} - \text{MPF}_{\text{before}}}{\text{MPF}_{\text{after}}} \times 100
\]

(2)

2.4. Statistical analysis

SamplePower 2.0 software (SPSS®, Inc. USA) was used to determine the number of participants in this study. The analysis used the mean and SD values of the extracted features with an alpha level of 0.05 and power at 84.6% was achieved. The percentage deviations extracted from MVC test and the slopes of RMS and MPF of sEMG signals extracted from real-time monitoring during on-road cycling were statistically analysed. The extracted features should be normally distributed set for parametric test. Normality test on the features-to-be-evaluated yielded a negative result. Hence, a non-parametric test (Friedman test) was performed on the features extracted from MVC test and on-road cycling, to evaluate the level of significance of muscle activity, riding among

![Fig. 2. Physical locations of the surface electrodes on a typical participant. Muscles that were examined included extensor carpi radialis (ECR); trapezius medial (TM); latissimus dorsi medial (LDM); erector spinae (ES).](image-url)
three bicycle designs. Post hoc analysis was performed using the Tukey multiple comparisons test and the significance level was set to \( p < 0.05 \) for all analysis. SPSS 15.0 for Windows (SPSS Inc., Chicago, IL) was used for the statistical calculations.

2.5. Psychophysical analysis

Self administered questionnaire study was conducted among all the participants to quantify the overall comfort levels at neck, shoulders, arms, hands, back and legs using RBG pain scale. The study was administered at the end of each experiment so that the participant could grade the perceived comfort or pain they experienced immediately after 30 min of cycling. RBG pain scale criteria and their corresponding grades are depicted in Table 1.

3. Results

3.1. MVC study

In the MVC study, statistical tests were able to significantly differentiate \( p < 0.05 \) the sEMG activity of right LDM and right ES muscle groups in SP bicycle when compared to RF and SU bicycles. There was a decrease in MPF value of right LDM muscle group in SP as compared to RF and SU (Fig. 4). Both time and frequency domain analysis indicated that the right ES was significantly fatigued \( p < 0.05 \) in SP over RF and SU bicycles (Figs. 5 and 6). This study illustrates that significant fatigue of left ECR muscle group in RF and SP in comparison with SU. RF bicycle had larger fatigue in right TM muscle group as compared to SU and SP (Fig. 7). It is interesting to note that there was no significant difference between SU and SP bicycles for the same muscle group.

3.2. On-road testing

Friedman test was performed for on-road test data. The slopes of both MPF and RMS versus time revealed a significant difference \( p < 0.05 \) between SP and SU for right ES. Besides, it was also evident that the scale of the fatiguing rate (negative slope for MPF and positive slope for RMS, versus time) was higher for the above mentioned muscle group in SP when compared to SU (Figs. 8 and 9). Thus, there was a significant positive rate of change of RMS with a concomitant negative rate of change of MPF in SP compared to SU bicycle design. In all other muscle groups considered in this study, no such appreciable difference was identified.

Table 1

<table>
<thead>
<tr>
<th>Grade</th>
<th>Pain scale criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No pain</td>
</tr>
<tr>
<td>1</td>
<td>Very minor, barely felt</td>
</tr>
<tr>
<td>2</td>
<td>Minor pain not interfering with the work routine</td>
</tr>
<tr>
<td>3</td>
<td>Moderate pain</td>
</tr>
<tr>
<td>4</td>
<td>Continuous pain affecting routine cycling</td>
</tr>
<tr>
<td>5</td>
<td>Unbearable/severe pain</td>
</tr>
</tbody>
</table>

Fig. 4. Mean and standard deviation error of % deviation in MPF of right latissimus dorsi medial muscle group calculated from before and after 30 min of bicycling (MVC test).
3.3. RBG pain score result

Pain scores from the psychophysical study, that is, RBG pain scale grading, are tabulated in Table 2. Perceived discomfort on riding SP bicycle in the mid back and low back muscle groups were significantly higher \((p < 0.05)\) from RF and SU bicycles. Additionally, the overall discomfort/pain score was also significantly higher \((p < 0.05)\) in SP bicycle.

4. Discussion

The purpose of the study was to determine the muscle activity of cyclists, riding on three different bicycle design concepts: RF, SU and SP bicycles using bilateral sEMG. Experiment duration was confined to 30 min of road cycling, since the average speed could not be maintained thereafter (Balasubramanian and Jayaraman, 2009). The performance observed on these bicycle configurations indicated that they were significantly different from each other; this is not to justify that each bicycle is not equally manoeuvrable. It is evident from the results of this study that each bicycle design exhibited a difference in muscle activity of the muscle groups chosen.

EMG-based studies rely on many parameters that are considered as a basis for evaluating fatigue: an increase in EMG signal amplitude or a decrease in the number of zero crossings (McLean et al., 1998), downward shifts in mean/median power frequency (Arendt-Nielsen and Mills, 1988; Srinivasan and Balasubramanian, 2007). In the present study, muscle activity was estimated in both the time and frequency domains by measuring the rate of decrease of MPF and the rate of increase of RMS. This study used percentage deviation in MPF and RMS to significantly differentiate the muscle activity before and after 30 min of cycling; slope of MPF and RMS to significantly evaluate the fatigue rate during on-road cycling on the three different bicycle designs.

Cycling in the dropped bar (SP bicycle) posture results in a significantly higher submaximal \(\text{VO}_2\) than cycling in the standard bar posture. The reason is that the arms, shoulder and lower back muscle groups are being engaged to a greater extent to overcome aerodynamic force. However, the mechanical work spent with SP bicycle is higher when riding with the rider crouched (Faria et al., 1978; Capelli et al., 2008). Kirkendall (1990) reported that fatigue ultimately results in reduced performance and function; thereby the present study confirmed the above-mentioned issues that in SP
bicycles, participants have reduced performance in right LDM and right ES muscle groups after 30 min of cycling when compared to RF and SU bicycles. The SP bicycle appeared to lead to a higher muscular fatigue among the three designs, corroborating this result is another study (Purswell et al., 1974) stating that SP (racing) bicycle offers the least manoeuvrability. Additionally, results from psychophysical analysis of our study provide corroborative evidence to the above findings (Table 2).

Graves (2000) reported that only minimal advantages could be expected using suspension systems on bumpy tracks, but the results were not conclusive. Hence, present study considered the physiological responses (sEMG activity) of cyclists riding on three bicycle designs. The main factors involving human response to vibration of bicycles are the vibration coming from the bicycle itself, the posture of the hands and arms during the gripping of the handlebars and the surrounding environment. Vibration is transmitted from the bicycle to the handlebars to the hand-arms and the body; from the saddle to buttocks, the waist, and the body and from the foot rest, the leg and the body. Karnopp and Margolis (1984) stated that for human response to vibration, the suspension should isolate the body from high frequency road profiles. At lower frequencies, the body and wheel should closely follow the vertical profile from the road to improve balancing. When bicycle wheels with spring suspension encounters a bump, the spring compresses, hence the force on the frame and cyclist is much smaller. Therefore, the potential benefits of a SU bicycle on a rough terrain are: reduced energy cost by the rider and better performance and comfort.

In SU bicycle, the left ECR, right LDM and right ES muscle groups have shown no significant fatigue and hence, considered comfortable to ride where the greater stability on the upper extremity and the back muscles were more likely to lead to better performance. In this study, right TM muscle group was significantly fatigued in RF when compared to SU bicycle. This result suggested that prolonged stretching of the hand for gripping the handlebar requires the participation of upper extremity and shoulder muscle groups. Since, in RF bicycle, the wheels are attached directly to the frame; when one of the wheels hits a bump, both that wheel and the frame must accelerate upward together. This exerts an enormous upward force on cyclist who experiences a sudden upward acceleration. To reduce the upward acceleration that the cyclist experiences, the direct connection between the bicycle wheels and the frame can be replaced by a spring suspension, i.e., SU bicycle design. As a result, the cycle frame and the cyclist do not bounce significantly when the wheel rides on irregular road surfaces.

The results of this study suggest that in SP bicycle, there is a significant fatigue in right LDM and right ES muscle groups, which ultimately shows that the cyclist experiences an asymmetry loading during prolonged cycling, caused by the dominance of the natural side, at work. All the participants in the study being right handed, the results eventually expressed a significantly higher fatigue in the right side when compared to the left.

### 5. Limitations of current study

In this study we have not performed a detailed postural and energy expenditure analysis of a rider while riding on different bicycle designs. Further, owing to cultural and other considerations, we had only male participants in this study. Future studies could take into consideration female participants and perform a detailed postural and energy expenditure analysis. In addition, the time at which fatigue is initiated can also be analysed. Future research on the effect of bicycle designs on bicycling performance over time can also be made. Familiarity of the participants with a particular type of bicycle should also be taken into account in the future studies.

### 6. Concluding remarks

The findings of this study indicate that there is a substantially higher muscular fatigue in upper extremity and low back muscle groups, which could reflect in poor balancing of bicycle while manoeuvring SP bicycle compared to RF and the SU bicycles. The results also suggest that the SU bicycle shows evidence of how well the suspension prevents muscular fatigue and vibration-induced low-back pain. These significant differences among the three bicycle designs have been demonstrated by means of MVC test before and after cycling and real-time monitoring of muscle activity during on-road cycling. This study helps to understand the variation of muscle activity caused by the mechanical factors of bicycle design. These inferences could be considered for ergonomics design of bicycle.

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### References


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