Design of a Bilaterally Asymmetric Pedaling Machine and its Measuring System for Medical Rehabilitation

Jinhua She[1,2,3], Fajian Wu[1], Hiroshi Hashimoto[4], Toshihiro Mita[1] and Min Wu[2,3]

[1]*Graduate School of Tokyo University of Technology, Hachioji, Tokyo 192-0982, Japan*

[2]*School of Automation, China University of Geosciences, Wuhan, Hubei 430074, China*

[3]*Hubei Key Laboratory of Advanced Control and Intelligent Automation for Complex Systems, Wuhan, Hubei 430074, China*

[4]*Master Program of Innovation for Design & Engineering, Advanced Institute of Industrial Technology, Shinagawa-ku, Tokyo 140-0011, Japan*

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Abstract: Most commercially available rehabilitation machines are bilateral symmetric. This makes it difficult to use for people with lower-limb injuries. This paper explains the design of a bilaterally asymmetric pedaling machine and its measuring system to solve this problem. Pedaling angles, strokes, and force of this machine can easily be adjusted independently for the left and right legs. Pedaling force and strokes, heart rate, and electromyogram (EMS) signals of walking muscles are recorded using a measuring system. This ensures the interaction between lower-limb exercises, and the computer-based supervision and control of medical rehabilitation. A prototype of a half model of the machine was built. Preliminary tests for the basic functions were carried out and demonstrated the validity of the machine and the measuring system.

1 INTRODUCTION

The number of the elderly (people aged 65 or older) in Japan was 34.63 million at October 1, 2016, which was 27.3% in the percentage of population (Statistics Bureau, 2016). Total spending of the nursing-care insurance system was 31.5 trillion yen in financial 2015, which was as high as 32.7% of the annual expenditure (Murayama, 2015). This caused a big burden for the society. Statistics shows that more than one in three Japanese will be the elderly and one in five will be 75 years old or older by 2025, and the number of people in Japan needing rehabilitation will be keeping increasing in the next decade. This has been called the 2025 problem (Ministry of Health, Labour and Welfare, 2016). It has been becoming imperative for the government to find a way to solve the nursing-care problem.

Walking is a basic action of daily life. Maintaining or improving the physical strength of walking muscles prevents the degradation of motor functions, and promotes the mental and physical health of the elderly. This eventually benefits the whole society.

Considering that pedaling is an effective exercise for the walking muscles, we developed a new-concept electric cart to integrate an exercise function into the ability of old people to get around (She et al., 2006). Unlike the commercially available carts, this one mounted a pedal unit on the cart. It has two pedals and a pedal motor that generates a pedal load for a driver. The speed of the pedal motor is determined by the driver's efforts, and constitutes a reference input for the cart. The speed of the cart motor tracks that reference. So, the experience is very similar to riding a bicycle. To improve the effectiveness of pedaling as a kind of exercise, we devised a mechanism that automatically selects a suitable load for the driver (She et al., 2013). And many other pedaling-type rehabilitation machines, for example, (Anzai, 2014), have also been developed. However, almost all of these machines have the following problems:

1. the pedaling loads and strokes are bisymmetric; and
2. the structure of the machines is fixed.

So, they are not suitable for people with asymmetrical ability for left and right limbs. As a result, people have to adapt themselves to the machines, or in other words, this kind of rehabilitation is machine centered. This not only may cause a great pain in rehabilitation,

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Table 1: Statistics of average leg-extension force while seated (numbers in parentheses are standard deviations) (Sato, 1994).

	One leg	Right leg	Left leg	Subject
Man	2729 (506)			46 Jap. univ. students at Dept. Health & Sport Sciences (18-24 y/o)
		2067 (498)	1897 (478)	Swedish
	2887 (506)			Dane
Woman		1260 (291)	1240 (303)	Swedish
	2133 (415)			Dane

but also may degrade the will to rehabilitation.

Some studies have taken the bilateral asymmetry into consideration. For example, the relationship between asymmetry and lower limb preference was examined (Carpes et al., 2010), and asymmetrical pedaling patterns in Parkinson's disease patients were measured in (Penko et al., 2014). However, they did not consider the asymmetrical problem from the viewpoint of the design of a rehabilitation machine.

To solve the problems, we developed a new kind of a pedaling machine for rehabilitation (She et al., 2016a; She et al., 2016b). Unlike other ones, it is human centered, that is, the structure of the machine is variable, and is adaptable to different lower-limb requirements. The pedaling loads and strokes can also be adjusted independently. This ensures the durability of rehabilitation and improve the efficiency of rehabilitation. The combination of a bilaterally asymmetric pedaling mechanism and a measuring system makes it possible to carry out the interaction between lower-limb exercises and the computer-based supervision and control of medical rehabilitation.

While the design of the mechanism of the pedaling machine was explained in (She et al., 2016a; She et al., 2016b), this paper explains the design of the machine and the measuring system for pedaling, and reports the results of some preliminary tests.

2 BASIC REQUIREMENTS FOR PEDALING EXERCISE AND MEASURING SYSTEM

The requirements for pedaling exercise are first considered.

Rehabilitation is basically divided into three stages: acute stage (1-14 days), recovery stage (up to several months), and functional stage (several months to years) (Dugan, 2006). This study focused on providing a means for the last stage, that is, for the functional stage.

Since pedaling is an effective exercise to train the walking muscles, we tried to build a new type of pedaling machine. There are two types of pedaling: rotational and linear. Considering that a rotational pedaling motion is basically bisymmetric, it is not suitable for people with lower-limb injuries. On the other hand, note that a linear pedaling motion can easily be used to design an asymmetrical mechanism to suit different requirements for left and right lower-limbs, we used it for the development of the rehabilitation machine in this study.

After fixing the pedaling mechanism, we turn to choose parameters for the pedaling. First, we select a pedaling force. Note that the maximum of the average leg-extension force of one leg is about 2900 N for young people (Table 1) (Sato, 1994). Since the leg strength reaches its peak at 20s and then it decreases with aging (Sato, 1994), and people who need rehabilitation have weak legs and are mainly in the middle aged and elderly, it is enough to choose the maximum force for pedaling to be

$$P_{\max} = 2000 \text{ N}. \quad (1)$$

Next, we select the parameters for pedaling stroke. As pointed out in (Sato, 1994), ergonomics shows that there is an optimal pedaling region. It is given in Figure 1 for the definitions in Figure 2. For the optimal region, the angle between the femur and the lower leg is in the range $[15°, 90°]$ when the knee is at the closest position to the body, and $[30°, 90°]$ when the knee at the farthest position from the body. Considering that a person needs rehabilitation may not sit and/or pedal properly as a normal person does, and referring to the results in (Timmer, 1991; Johnston, 2007), we chose the angle between the femur and the lower leg to be

$$\theta \in [0°, 90°]. \quad (2)$$

Equation (2) provides us a larger region than the optimal one. This gives us a big freedom to suit different kinds of requirements.

The stroke of a linear motion should also be chosen to be long enough. It was chosen to be

$$L = 150 \text{ mm} \quad (3)$$

based on a preliminary test.

As for the design of the measuring system, the following points need to be considered:

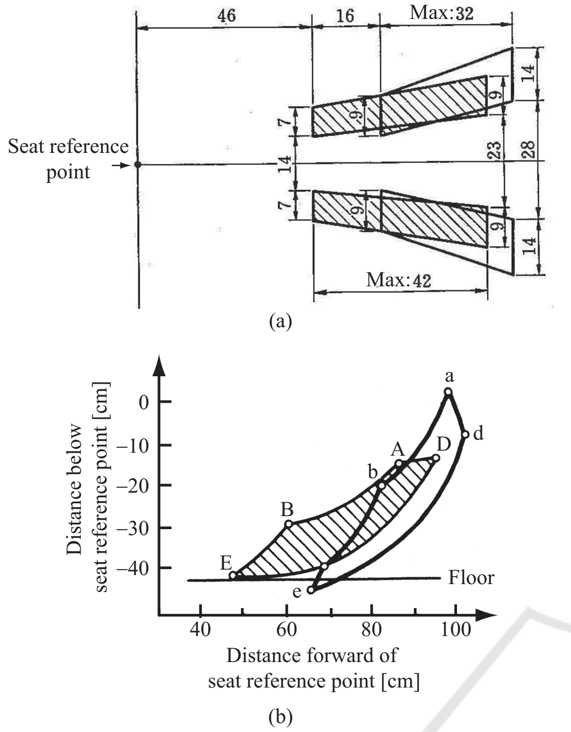

Figure 1: Optimal pedaling region. (a) Top view and (b) Side view (Upper case: heel. Lower case: toe) (Sato, 1994; She et al., 2006).

- Measured data are suitably stored in a real-time fashion.
- Measured data can easily be accessed.
- Measured data are displayed in a real-time fashion, and it is easy to switch to the display of interested data.
- Data can be synchronized if needed.

3 DESIGN OF PEDALING MECHANISM AND MEASURING SYSTEM

A pedaling mechanism is designed in this section that satisfies the requirements given in Section 2.

An oil damper, KINECHECK Super K (Meiyu Airmatic Co. Ltd., Japan) (Table 2) was selected to provide a pedaling load. It produces the largest damping force, and has the longest stroke in the class of small dampers. While the maximum force is more than the double of $P_{\max}$ in (1), the stroke is only 70% of L in (3). To ensure that the requirements (1)-(3) are satisfied, a half model of a pulley-type pedaling mechanism was designed in Figure 3. It enlarges the stroke doubly and reducing the load force to half. To ensure (2), an adjusting part was designed and installed in the machine. The inclined angle of the adjusting part can be changed from 0° to 90°. A prototype of the pulley mechanism for one leg was first built for evaluation (Figure 5).

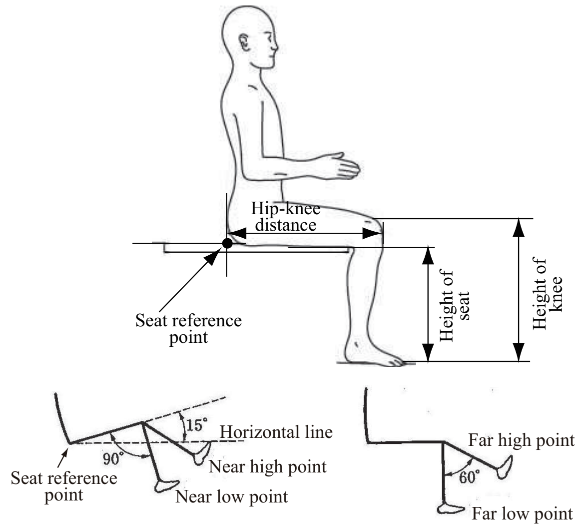

Figure 2: Definitions (Sato, 1994; She et al., 2006).

Table 2: Parameters of oil damper, KINECHECK Super K.

Model	Overall length	Stroke	Force range
5001-31-4	356 mm	102 mm	23 $\sim$ 5440 N

As for the measuring system, we chose the heart rate meter to be neo HR-40 (NISSEI Co. Ltd., Japan), the force sensor to be LPR-C-1KNS15 and the displacement sensor to be DTS-A-100 (Kyowa Electronic Instruments Co. Ltd., Japan), and the wireless EMS sensor to be SX230-1000 and a 9-axes wireless motion sensor (XYZ geomagnetism, XYZ acceleration, and XYZ angular acceleration) (DKH, Japan). And we constructed the measuring system as shown in Figures 4 and 6.

The measuring system is used to supervise exercises and to perform the interaction between the exercises and the computer-based control of rehabilitation. It is important to select a suitable pedaling load for a user based on the user's physical condition. In this study, a suitable load means a pedaling load that does not seem heavy or light and can safely be used for endurance training (U.S. Dept. of Health and Human Services, 2008). This human-computer interaction not only maintains the motivation for rehabilitation, but also results in enhanced exercise outcomes in the long term.

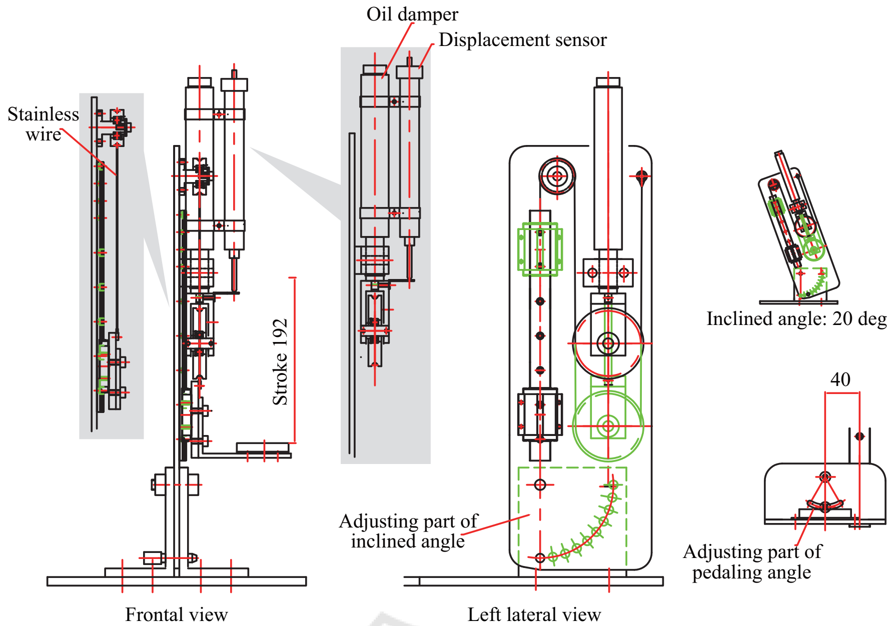

Figure 3: Pulley-type pedaling mechanism (half model).

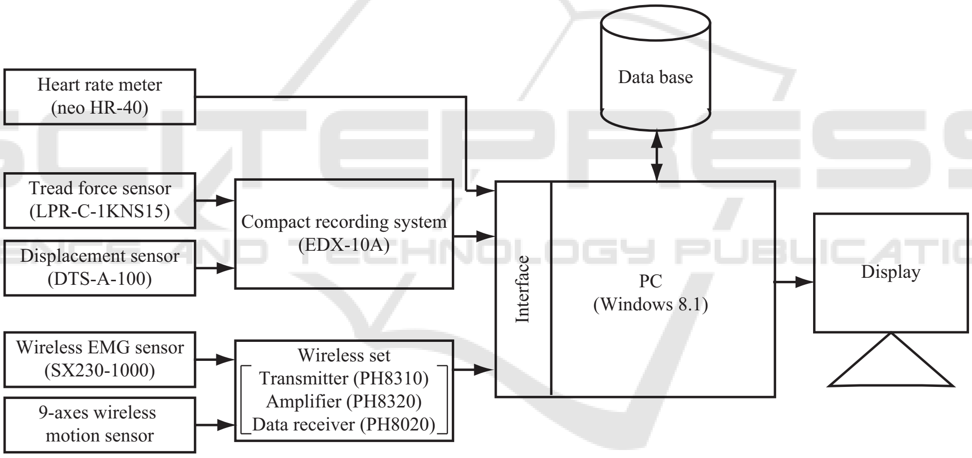

Figure 4: Measuring system.

4 PRELIMINARY TESTS

Preliminary tests were carried out for the half model and the measuring system for three subjects. The pedaling force was set in the range of 0-270 N (Level 0: 23 N; 3: 50 N; 6: 90 N; 9: 140 N; 12: 200 N; and 15: 270 N); and the angle of the inclined angle adjusting part, 0-90°. The sampling period of the measuring system was set to be 0.02 s. Test results show that the machine and the measuring system worked well as designed. The sensors produced outputs correctly for all the pedaling activities. It was found that pedaling was carried out smoothly and comfortably for the inclined angle in the range $[40^\circ, 70^\circ]$. Some typical pedaling results are shown in Figure 7. As shown in the figure, the pedaling period is the shortest and the pedaling force is the largest for 60° among the three angles. This indicates that the inclined angle of 60° is the easiest one for pedaling.

Among the measured four EMG signals (quadriceps femoris, biceps, soleus, and tibialis anterior), that of quadriceps femoris is the largest, and that of soleus is the smallest (Figure 8).

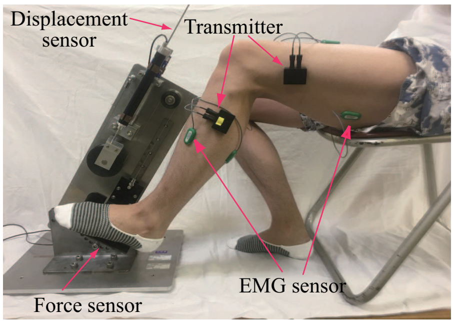

Figure 5: A photo of experimental system.

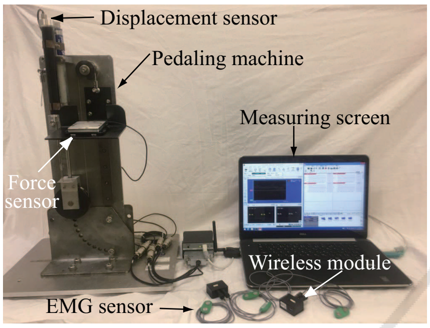

Figure 6: A photo of some components of measuring system.

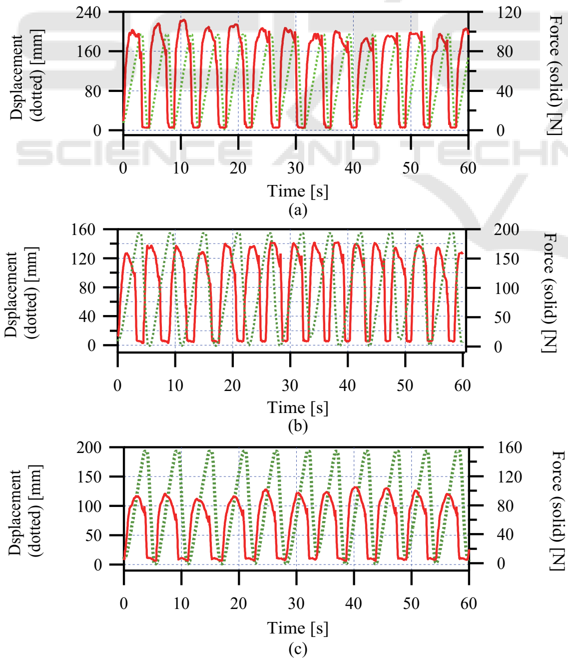

Figure 7: Pedaling results for Load 9 (140 N) and inclined angle of (a) 40°, (b) 60°, and (c) 80°.

5 CONCLUSION

A new type of a bilaterally asymmetric rehabilitation machine and its measuring system were designed in this study. The machine is a linear pedaling type. This ensures that a user can easily and independently adjust the pedaling pose, pedaling displacement, etc. in an asymmetrical fashion. Preliminary tests for the basic functions have been tested, and the test results demonstrated the feasibility of the machine.

We planned to use the mechanism and the measuring system to carry out the verification of the effectiveness of the system for the rehabilitation of lower limbs, and to examine the interaction between lower-limb exercises, and the computer-based supervision and control of medical rehabilitation. The performance indexes used in (Smak et al., 1999; Carpes et al., 2010) will be integrated to evaluate the lateral asymmetry and the effectiveness of pedaling for rehabilitation. Now, we are collecting normal subjects (mainly university students) to carry out a full test for the prototype. Then, we plan to investigate the effect of rehabilitation from the viewpoints of human-computer interaction, physiotherapy, exercise psychology, etc. After the analysis, we plan to invite

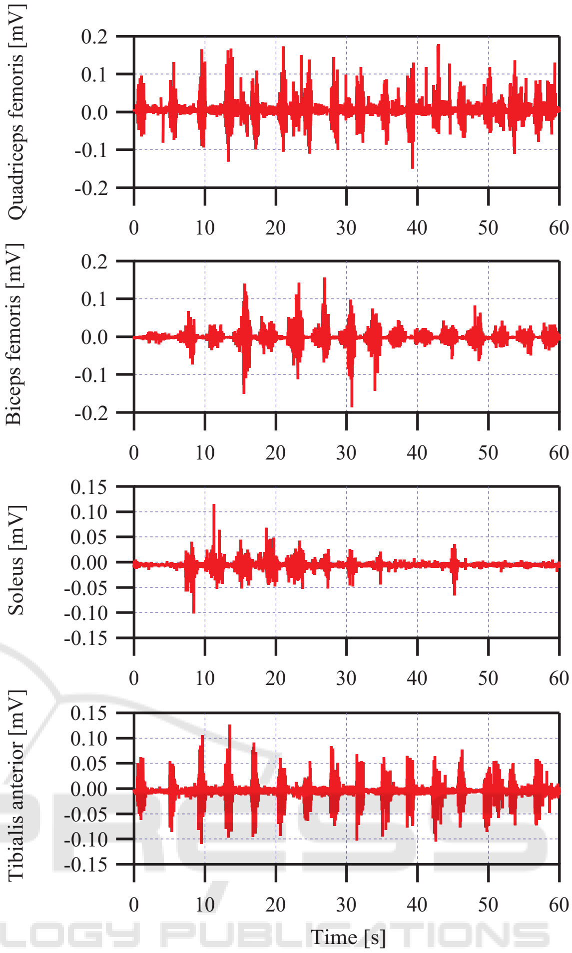

Figure 8: EMG signals for Load 9 (140 N) and inclined angle of 60°.

people with lower-limb injuries to test the effectiveness of the system. Those results will be reported in the near future.

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REFERENCES

S. Anzai (2014). Healthy Cycle: A Leg-Powered Wheelchair from Japan Is Motivating the Disabled, *Highlighting Japan*, no. 11, pp. 20-21. Available: http://dwl.gov-online.go.jp/video/cao/dl/public_html/gov/pdf/hlj/20141101/20-21.pdf

F. P. Carpes, C. B. Mota, and I. E. Faria (2010). On the bilateral asymmetry during running and cycling – A review considering leg preference *Physical Therapy in Sport*, no. 11, pp. 136-142.

S. A. Dugan (2006). Exercise in the Rehabilitation of the Athlete, in *W. R. Frontera, S. A. Herring, L. J. Micheli, and J. K. Silver Ed., Clinical Sports Medicine: Medical Management and Rehabilitation*, Saunders, Elsevier.

Ministry of Health, Labour and Welfare (2016). *Survey of Long-term Care Benefit Expenditures*, Available: http://www.mhlw.go.jp/english/database/db-hss/soltcbe.html

T. E. Johnston (2007). Biomechanical Considerations for Cycling Interventions in Rehabilitation, *Physical Therapy*, vol. 87, no. 9, pp. 1243-1252

H. Murayama (2015). Nani ga zaiseiakazi kakudai no gennin ka (What's the cause of the expansion of the fiscal deficit) *Economic Report*, Available: http://www.kyotobank.co.jp/houjin/report/pdf/201505_02.pdf

A. L. Penko, J. R. Hirsch, C. Voelcker-Rehage, P. E. Martin, G. Blackburn, and J. L. Alberts (2014). Asymmetrical pedaling patterns in Parkinson's disease patients, *Clinical Biomechanics*, vol. 29, pp. 1089-1094.

M. Sato (1994). *Ningen Kougaku Kijun Suuchi Suushiki Benran (Handbook of ergonomic standards, numerical values, and formulas)*, Tokyo: Gihodo Shuppan Co., Ltd.

Statistics Bureau (2016). *Monthly Report: Population Estimates by Age (5-Year Age Group) and Sex*, Available: http://www.stat.go.jp/english/data/jinsui/tsuki/index.htm

J. She, Y. Ohyama, and H. Kobayashi (2006). Master-Slave Electric Cart Control System for Maintaining/Improving Physical Strength, *IEEE Trans. Robot.*, vol. 22, no. 3, pp. 481-490.

J. She, S. Yokota, and E. Y. Du (2013). Automatic heart-rate-based selection of pedal load and control system for electric cart, *Mechatronics*, vol. 23, pp. 279-288.

J. She, F. Wu, T. Mita, H. Hashimoto, and M. Wu (2016a). Design of a New Human-Centered Rehabilitation Machine, *Proc. 9th ACM Int. Conf. Pervasive Technologies Related to Assistive Environments (PETRA 2016)*, Corfe, Greece.

J. She, F. Wu, T. Mita, H. Hashimoto, and M. Wu (2016b). Design of Human-Centered Rehabilitation Machines for Lower Limbs, *Proc. IEEE-NIH 2016 Special Topics Conf. Healthcare Innovations and Point-of-Care Technologies (HI-POCT 2016)*, Cancun, Mexico.

W. Smak, R. R. Neptune, and M. L. Hull (1999). The influence of pedaling rate on bilateral asymmetry in cycling, *J. Biomechanics*, vol. 32, pp. 899-906.

C. A. W. Timmer (1991). Cycling Biomechanics: A Literature Review, *J. Orthopaedic & Sports Physical Therapy*, vol. 14, no. 3, pp. 106-113

U.S. Dept. Health and Human Services (2008). *Exercise: a guide from the national institute on aging*, National Institute of Health. Available: http://www.nia.nih.gov/