Design and Simulation of Wheel-chaired Elliptical Stepping Exercise for Stroke Rehabilitation

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Abstract— **Stroke disease is one of the major killer diseases worldwide and most of the survivors will end with certain level of impairment. They commonly are wheelchair bounded and require scheduled rehabilitation exercise to regain their walking capability or mobility. This paper presents the design of elliptical stepping exercise ergometer for functional electrical stimulation (FES) assisted exercise. The concept of wheel-chaired cycling and elliptical stepping had been adapted in producing the ergometer design. The dynamic simulation has been performed on Visual Nastran 4D and Matlab Simulink to evaluate the performance of the exercise that includes the exercise ergometer, humanoid model and quadriceps muscle model. In the simulation work, the paretic leg (left side) is driven via FES-assisted while the non-paretic leg (right side) is driven via controlled knee joint torque. The result shows that the FES-assisted elliptical stepping exercises with voluntary non-paretic movement contribute better cadence speed control. Further improvement on the controller design is required to make sure suitable FES pattern can be delivered and better cadence speed control can be achieved in simulation environment as well as real implementation.**

I. Introduction

CURRENT trend shows the stroke disease as one of the major killer worldwide after heart disease and cancer. According to UMDNJ [1], 15 % of stroke disease victims die shortly after stroke and the rest 75% are survivors with different level of impairment. The most common effect of stroke disease is weakness or paralysis on one side of the body which is called hemiparesis or hemiplegia and it may affect the face, an arm, a leg or all three areas, and can range from mild weakness to total loss of movement [2]. Rehabilitation process helps the stroke patients getting back to their normal life by achieving the best level of independence [3]. Studies in [4] and [5] agreed that physical exercise training has potential to encourage the function regaining and prevent recurrent stroke. There is a strong consensus among rehabilitation experts that the most important element in any rehabilitation program is carefully directed, well-focused and repetitive practice [8]. On the other side, studies in [6] and [7] have mentioned that degradation of muscle mass is the consequences of inactivity, poor fitness and physical performance capacity after stroke. The muscle mass degradation can cause the muscles losing its strength and experience rapid muscle fatigue during movement. With this reason, structured rehabilitation exercise need to be planned which can suit to the patient’s functional loss condition. This is important to maintain the muscle activity, to encourage the recovery to occur and to avoid degradation of muscle mass due to inactivity.

Functional electrical stimulation (FES) to restore movement in paralyzes or weak individuals have been regarded for decades as feasible way of rehabilitation. As each decade brings new innovations in electronics and microprocessor, better and more controlled systems become possible [9]. Since the first application introduced by Liberson [10] for foot drop, the application of FES has evolved until this decade and the research on it is still significant with the introduction of new ideas in term of the way it is implemented. FES has also been implemented in many ways of exercise technique mainly for spinal cord injuries (SCI) and stroke rehabilitation such as ankle movement [11],[12] rowing exercise [13],[14] and cycling exercise [15]-[17].

Most of stroke survivors are wheelchair bounded and restricts their activities especially in performing scheduled rehabilitation exercise using specified ergometer. The difficulty includes the transfer from wheelchair to the ergometer. Wheelchair accessed ergometer is seemed to be the solution and product such as berkelbike and RT-300 are the available commercial product for cycling exercise. Gait like exercise movement such as elliptical stepping offers good benefit in rehabilitation. The design of elliptical stepping exercise provides over wide range of exercise intensity while minimizing the potential for lower extremity injuries [18]. Previous findings reported that elliptical stepping resulted better muscle activity compared to cycling [19],[20] and better heart rate and oxygen consumption compared to walking, biking, stepping and running [18].

This paper presents the new design of wheel-chaired elliptical stepping exercise ergometer and the performance evaluations. With this ergometer, subject (stroke patient) can perform the exercise directly from wheelchair and avoid the difficulty of body transfer from wheelchair to ergometer seat. Upper and lower body also can cooperate when performing upper body assisted elliptical stepping exercise on this ergometer. The findings in this paper can support the implementation of this proposed exercise ergometer for

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stroke rehabilitation with further investigation will be focused on improving the exercise technique and FES control strategy.

II. METHODOLOGY

A. Ergometer Design Concept

The concept of wheel-chaired cycling and elliptical stepping were adapted in the design of wheel-chaired elliptical stepping exercise ergometer. The elliptical stepping movement is totally driven by both legs with an optional arm handle for arm assistant during exercise. Flywheel of 8Kg in weight is fitted at the crank arm shaft and act as rotational energy storage to deliver extra energy when it rotates. Bolund et al. [21] described that depending on the inertia and speed of the rotating mass, a given amount of kinetic energy is stored as rotational energy. This energy can be used to maintain the exercise movement at the dead spot. Dead spot is generally located at 0° and 180° of crank arm position and is defined as the point of transition between applying extension moment and flexion moment [22]. In the design, the flywheel was suspended by a bearing to allow it to move smoothly at low friction. Crank arm was designed to have 16cm in length which will result with 32cm of stepping length. This small stepping length is considered fit with most of the subject's body height when performing the exercise from wheelchair. The mechanism of the wheel-chaired elliptical stepping exercise is illustrated in Fig. 1.

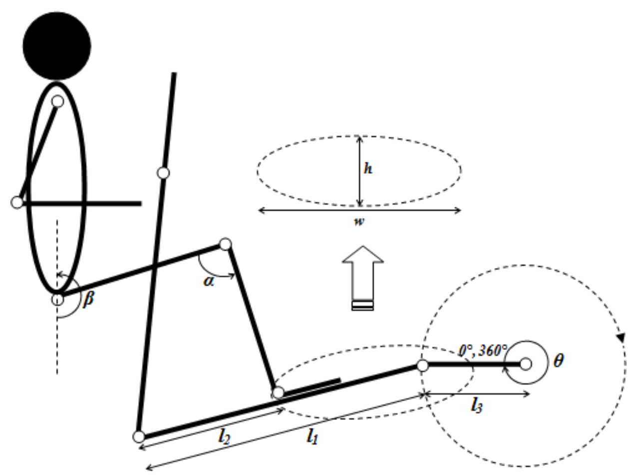

Fig. 1. The mechanism of wheel-chaired elliptical stepping exercise

The symbol denotes the important parameters which comprise of length and angle of the component in the mechanism and can be detailed as follows:

h : elliptical stepping height
w : elliptical stepping length

The size of the elliptical stepping is varies according to the parameter l_1, l_2 , and l_3 and the step length and height of the elliptical stepping is denotes by h and w which can be determined as follows:

$$h = \frac{l_2}{l_1}(2l_3) \quad (1)$$

and

$$w = 2l_3 \quad (2)$$

where,
l_1 : ergometer stepping arm length
l_2 : foot position on the ergometer stepping arm
l_3 : ergometer crank arm length

In the implementation of closed-loop control, feedback parameter is very important in order to deliver the information from the output to the input of the system. Hence, three feedback parameters are involved in the study which denotes by:

α : knee joint angle
β : hip joint angle
θ : flywheel position angle

The flywheel position angle, θ is collected through sensor interface and feed into the developed controller in Matlab Simulink. In this simulation work, θ is collected directly from the angular position meter that is used in the simulation. The flywheel position angle is used to determine the correct leg position for stimulation. θ is also converted into the cadence speed, θ' in term of revolution per minute (rpm). Both parameters, θ and θ' are very important to make sure the developed control system in the control platform (in this case matlab simulink) received sufficient information in order to produce appropriate control signal. The concept of FES-assisted exercise with voluntary non-paretic movement is proposed in the exercise movement control. Hence, controlled knee joint torque is applied to the non-paretic leg (right side) to mimic the voluntarily movement, whereas the paretic leg (left side) is driven by controlled FES.

The simulation model of the elliptical stepping exercise which include the exercise ergometer, humanoid and wheelchair model was developed on Visual Nastran 4D and linked to Matlab Simulink for the purpose of control. Detail explanation on the model development and validation analysis was presented in [23]. The developed model is shown in Fig. 2. Further improvement has been made to the model by incorporating the muscle model to the left leg to mimic the paretic side of stroke patient. For this purpose, quadriceps muscle model has been developed based on algorithm developed by Reiner and Fuhr [24]. The two muscles involved in quadriceps that are rectus femoris and vasti muscle have been developed. The contraction of rectus femoris will cause knee extension movement and hip flexion movement, whereas contraction of vasti will only cause knee extension. Hence, the sum output torque, T from the stimulation of quadriceps muscle is knee joint torque and hip joint torque. Detail on the muscle model development and the simulation test was presented in [25]. The method of movement control of the left leg with muscle model is shown in the block diagram of Fig. 3.

The muscle model requires two inputs that are stimulation frequency (f) and stimulation pulse width (d), and will produce joint torque at the output. The quadriceps muscle model is linked to the left knee and hip joint to represent the paretic leg of stroke patient. Fixed pattern of FES is set to 200µs of pulse width and 30Hz of frequency. The FES is delivered between 0° to 180° of the crank arm position when error of the cadence speed is positive. For this model, the desired cadence speed is set to 30 rpm. Since the right leg is acted as non-paretic leg, hence no muscle model linked to it. The movement of the right knee joint is controlled by Proportional Derivative (PD) controller and cadence speed error is used as the controller input. Based on trial and error study, the PD gain is set to 5.2 for kp and 0.01 for kd. At this control gain, smooth cadence of the elliptical stepping movement has been achieved.

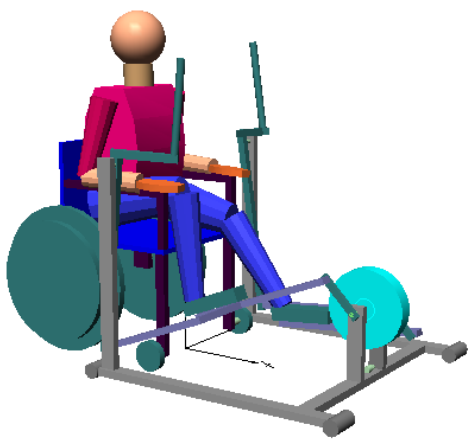

Fig. 2. Simulation model of wheel-chaired elliptical stepping exercise

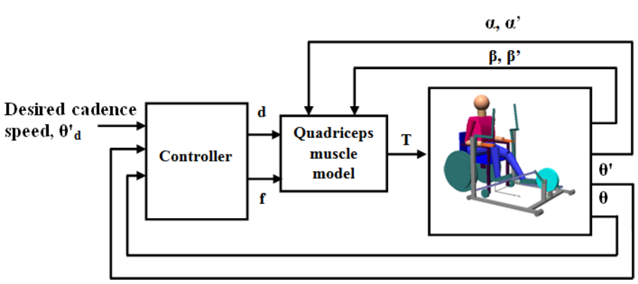

Fig. 3. Block diagram of left leg movement control with muscle model

III. SIMULATION RESULT

Fig. 4 shows the simulation result which comprise of knee joint torque, flywheel position angle and cadence speed error. At positive error of cadence speed, FES is applied to the quadriceps muscle of the left leg between 0º to 180º of crank arm position. The same applies to the right leg however no quadriceps muscle model linked to it. Noted that the movement is starts by left leg, thus if referred to the flywheel position angle, left leg will drive the movement at flywheel position angle of 0° to 180°, whereas right leg will drive the movement at flywheel position angle of 180° to 360°.

Fig. 4(a) shows the knee joint torque produced at both left and right knee for two cycles of elliptical stepping movement. The left knee joint torque is the result of stimulating the quadriceps muscle with FES at 200μs of pulse width and 30Hz of frequency. The maximum left knee joint torque required to perform the movement was recorded at 16.3Nm. The right knee joint torque is the result of applying controlled torque directly to the right knee joint (to mimic the voluntary movement of non-paretic leg). Since the control signal is amplified from the cadence speed error, the right knee joint torque that is proportional to the applied control signal was slightly higher at the beginning of stimulation and slowly decreased when the cadence speed error gets reduced. The maximum right knee joint torque required to perform the movement was recorded at 26.23Nm. This amount of torque is considered low if compared to the maximum of 50Nm to perform the movement of rowing [26] that was simulated the same way. This indicates that the wheel-chaired elliptical stepping exercise require much lower knee joint torque if compared to rowing exercise. Furthermore, elliptical stepping also activated all the lower extremity body segments of the subject that may benefit in term of rehabilitation as what obtained in rowing exercise.

Fig. 4(b) shows the flywheel position angle resulted from the movement driven by the left and right knee joint torque. Noted that, the flywheel position angle will increase linearly when smooth cadence speed control is achieved. The dotted line separates between the left leg driven (0° to 180°) and the right leg driven (180° to 360°) of the movement. Comparing both legs, better cadence speed control was obtained when the movement is driven by the right leg. This can be observed in Fig. 4(c) where the average absolute error was 11 rpm and 2.4 rpm for the movement driven by left and right leg respectively.

Fig. 5 shows the cadence speed error when the quadriceps muscle of the left leg is stimulated with different pulse width and frequency of FES. As can be observed, increasing the frequency doesn't much effect to the torque production and cadence speed error. This in line with Reiner [27] that described the muscle force saturated when stimulating with frequency above 30Hz. However, adjusting the pulse width has significant effect to the torque production. The cadence speed error has drastically increased which indicates that the left knee has produced high torque that caused overshoot during the movement. Since the muscle property is very unique from one subject to another, implementation of appropriate control strategy is very important to ensure the delivered FES always suited to the subject's muscle.

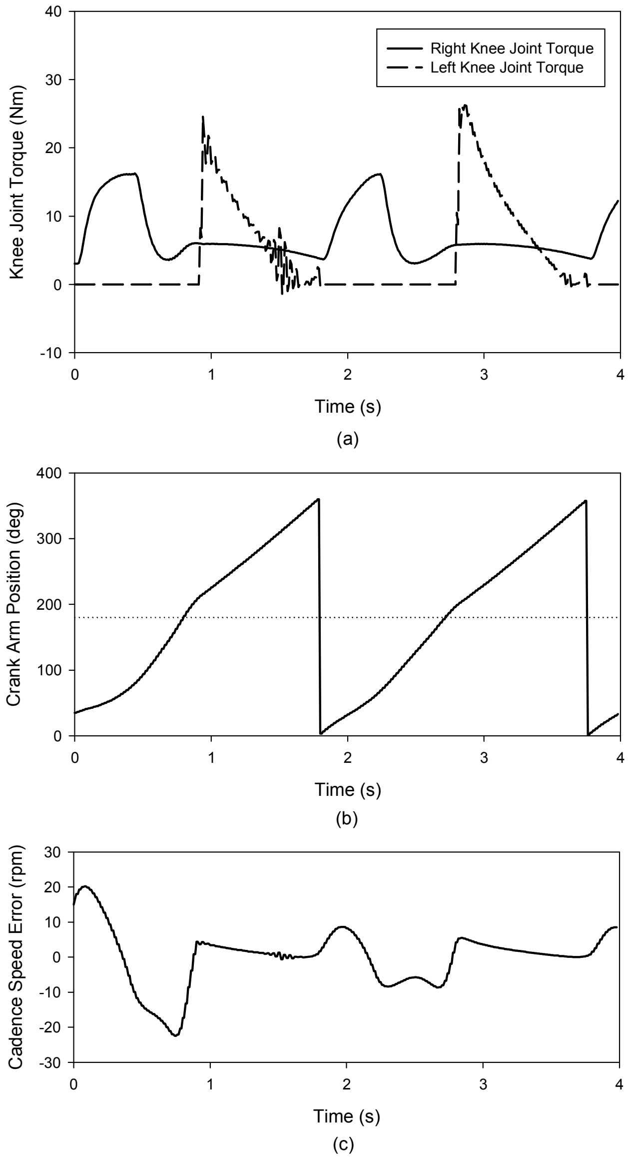

Fig. 4. Simulation response for desired cadence speed = 30rpm, pulse width=200*us*, frequency=30Hz (a) Knee joint torque (b) Flywheel position angle (c) Cadence speed error

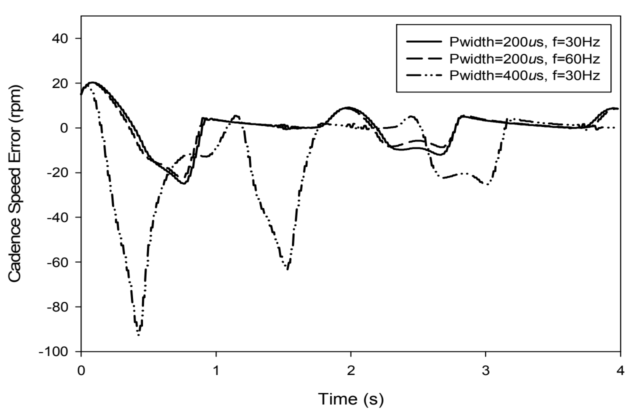

Fig. 5. Cadence speed error of different pulse width and frequency setting

IV. Conclusion

The present study has described the design of wheelchaired elliptical stepping exercise ergometer and the simulation of the exercise with humanoid model and quadriceps muscle model. The result shows the importance of controlling the FES that involves pulse width and frequency to cater the nonlinearity of the muscle in order to obtain the smooth exercise movement. In FES-assisted exercise movement, the result also shows the importance of coordination between non-paretic and paretic leg in order to achieve smooth exercise movement.

The nonlinearity of the muscle can cause the amount of torque varies as time increase. This mainly contributed by the muscle fatigue for a long stimulation period. Electrically stimulated muscle may suffer rapid muscle fatigue compared to voluntary muscle contraction. This situation is not avoidable but can be reduced by ensuring low FES intensity and short period of stimulation time are used to perform the desired movement. Stroke rehabilitation exercise concept that is represented in this work can ensure the above solution to be achieved. The future aim in this work is to investigate the new control strategies to appropriately control the FES and hence improve the efficiency of the exercise technique. Validation of the design on the healthy subject and stroke patient also will be performed as an effort towards the clinically acceptance of the system.

References

[1] G Website article, The University of Medicine & Dentistry of New Jersey (UMDNJ).
url: http://www.theuniversityhospital.com/stroke/stats.htm, retrieved on 26 Jan 2013.

[2] "Understanding Stroke Fact Sheet." BrainLink in association with MSSV, MNDAV, MDA, Parkinson's Victoria & AHDA (Vic), 2006.

[3] "Stroke Rehabilitation." The Stoke Assocciation, Scriptographic Publications Ltd. 2006.

[4] Rimmer J. H. and Wang E. "Aerobic Exercise Training in Stroke Rehabilitation", Topics in Stroke Rehabilitation, 12(1), pp. 17–30, Book Chapter of Winter 2005, Thomas Land Publishers Inc, 2005.

[5] Banks G., Bernhardt J., Churilov L. and Cumming T. B. "Exercise Preferences are Different After Stroke." Stroke Research and Treatment, Hindawi Publishing Corporation, Vol. 2012, Article ID 890946, pp. 1-9, May 2011.

[6] National Institute of Neurological Disorders and Stroke, National Institutes of Health, Bethesda. "Post Stroke Rehabilitation." URL: http://www.ninds.nih.gov. Last updated 26 July 2011.

[7] Hafer-Macko C. E., Ryan A. S, Ivey F. M. and Macko R. F. "Skeletal Muscle Changes After Hemiparetic Stroke and Potential Beneficial Effects of Exercise Intervention Strategies." Journal of Rehabilitation Research and Development, Vol. 45 No. 2, pp. 261-272, 2008.

[8] Ryan A. S., Ivey F. M., Prior S. P., Li G. and Macko C. H. "Skeletal Muscle Hyperthrophy and Muscle Myostatin Reduction After Resistive Training in Stroke Survivors." Journal of the American Heart Association, Vol. 42, pp. 416-420, 2011.

[9] Jones R., Smith A. D., Nuyens G., Whitlock T., Peasegood W., Ketelaer P. and Bateman A. "Functional Electrical Stimulation for Foot Drop in Multiple Scheloris". The Institution of Electrical Engineers, 1997.

[10] Liberson W, Holmquest H, Scott M. (1961). Functional electrotherapy: Stimulation of the common peroneal nerve synchronised with the swing phase of gait of hemiplegic subjects. *Arch Phys Med Rehabil* 42. 202-205

[11] Kobravi H. R. and Erfanian A. "Decentralized Adaptive Robust Control Based on Sliding Mode and Nonlinear Compensator for the Control of Ankle Movement using Functional Electrical Stimulation of Agonist-Antagonist Muscles". Journal of Neural Engineering, Vol 6, Pp. 1-10. 2009.

[12] Nekoukar V. and Erfanian A. "Adaptive Terminal Sliding Mode Control of Ankle Movement Using Functional Electrical Stimulation of Agonist-Antagonist Muscle". 32nd Annual International Conference of the IEEE EMBS, Buenos Aires, Argentina, pp. 5448-5451. 2010.

[13] Miyawaki K., Iwami T., Chikusa-ku H., Shimada Y., Matsunaga T., Sato M., "Development of FES-Rowing Machine," 29th IEEE Annual International Conference of the Engineering in Medicine and Biology Society (EMBS 2007), pp. 2768-2771, 22-26 Aug. 2007.

[14] Hussain, Z.; Tokhi, M.O.; Jailani, R.; Ahmad, S.; Ibrahim, B.S.K.K.; , "Effect of Inclined Rowing Machine on FES-Assisted Indoor Rowing Exercise Performance," Third Asia International Conference on Modelling & Simulation (AMS '09), pp. 242-245, 25-29 May 2009.

[15] Chien C. C., Zong C. H. and Ya H. H. "An EMG Feedback Control Functional Electrical Stimulation Cycling System" Journal of Signal Processing System 64, pp. 195-203, Springer, 2009.

[16] Kenneth J. H., Harry S., Negard N. O., Thomas S., Matthew H. F., Andrew J. C., Chiara F., Susan A. W. and Stan G. "Control Strategies of Integration of Electric Motor Assist and Functional Electrical Stimulation in Paraplegic Cycling: Utility for Exercise Testing and Mobile Cycling." IEEE Transactions on Neural Systems and Rehabilitation Engineering, Vol 12, No. 1, pp. 89-101, March 2004.

[17] Fornusek C., G. Davis G. M., Sinclair P. J. and Milthorpe B. "Development of an Isokenetic Functional Electrical Stimulation Cycle Ergometer." International Neuromodulation Society, Vol 7, No. 1, pp. 56-64, 2004.

[18] Porcari J., Foster C. and Schneider P. "Exercise Response to Elliptical Trainers." Fitness Management Article, August 2000.

[19] Hamzaid N. A., Pithon K. R., Smith R., and Davis G. M. "Functional electrical stimulation elliptical stepping versus cycling in spinal cord-injured individuals." Journal of Clinical Biomechanics Vol. 27, pp. 731-737, 2012.

[20] Prosser L.A., Stanley C.J., Norman T.L., Park H.S. and Damiano D. L. "Comparison of Elliptical Training, Stationary Cycling, Treadmill Walking and Overground Walking Electromygraphic Patterns." Journal of Gait and Posture, Vol. 33, pp. 244-250, 2011.

[21] Bolund B., Benhoff H. and Leijon M. "Flywheel energy and power storage systems." Renewable and Sustainable Energy Reviews Vol. 11 pp. 235-258, 2007.

[22] Jia-Jin J. Chen, Nan-Ying Yu, Ding-Gau Huang, Bao-Ting Ann and Gwo-Ching Chang "Applying Fuzzy Logic to Control Cycling Movement Induced by Functional Electrical Stimulation." IEEE Transactions on Rehabilitation Engineering, Vol. 5 No. 2, 1997.

[23] S.Z. Yahaya, Z. Hussain, R. Boudville and M.N Taib. "Dynamic Modeling and Control of Wheel-chaired Elliptical Stepping Exercise." Proceeding of the IEEE International Conference on Control System, Computing and Engineering, pp. 204-209 Penang, Malaysia, 2012.

[24] Riener R. and Fuhr T. "Patient-Driven Control of FES-Supported Standing Up: A Simulation Study" IEEE Transactions on Rehabilitation Engineering, Vol. 6, No. 2, June 2008.

[25] S.Z. Yahaya, Z. Hussain and R. Boudville. "Electrically Stimulated Quadriceps Muscle Model for Wheel-chaired Elliptical Stepping Exercise, Fifth International Conference on Computational Intelligence, Communication Systems and Networks, Madrid Spain, pp. 115-119, 5-7 June 2013.

[26] Z. Hussain, M.O. Tokhi and S. Gharooni. "Dynamics Simulation of Indoor Rowing Exercise for Paraplegics." Second Asia International Conference on Modeling and Simulation, pp. 901-904, 2008.

[27] Riener R. "Model Based Development of Neuroprostheses for Paraplegic Patients." Philosophical Transactions of the Royal Society Biological Sciences, No. 354, pp. 877-894, 1999.