Department of
Veterans Affairs

Journal of Rehabilitation Research and
Development Vol. 36 No. 1, January 1999
Pages 48-54

Augmentation of the 100 kg ISO wheelchair test dummy to accommodate higher mass: A technical note

Rory A. Cooper, PhD; Thomas J. O'Connor, MS; Jess P. Gonzalez, BS; Michael L. Boninger, MD; Andrew Rentschler, BS

Departments of Rehabilitation Science and Technology, Mechanical Engineering and Bioengineering, University of Pittsburgh, Pittsburgh, PA, 15261; Human Engineering Research Laboratories, VA Pittsburgh Health Care System, Pittsburgh, Pennsylvania, 15206; Division of Physical Medicine and Rehabilitation, Department of Orthopaedic Surgery, University of Pittsburgh Medical Center, Pittsburgh, PA, 15261

Abstract—Most of the 22 approved or developing ISO standards rely on a wheelchair test dummy, a specialized device described in ISO 7176-11. The purpose of this study was to develop a means for modifying the design of the ISO 7176-11 test dummy to be suitable for testing with higher masses. The changes are based upon published data for obese individuals. With these data, we derived equations for determining the distribution of the additional mass among the test dummy components, and the locations of the centers of mass. The results of this study provide guidelines for adding mass to the 100 kg wheelchair test dummy to accommodate testing of wheelchairs designed for obese individuals.

Key words: *anthropometry, quality, standards, test dummies, wheelchairs.*

INTRODUCTION

There are currently 22 International Organization for Standardization (ISO) wheelchair standards either approved or in development (1). Their purpose is to permit reasonable comparison of products and to ensure a minimum level of safety and quality. Most of these standards rely on a wheelchair test dummy, a specialized device described in ISO 7176-11. The 100 kg (95th percentile person) test dummy is the most commonly used (1-3), largely because it presents the worst-case loading scenario. However, Working Group One of Subcommittee One of Technical Committee 173 of ISO has recently decided that accommodations need to be made for test dummies of higher mass (4).

Such test dummies are required to properly load wheelchairs designed for users whose mass is in excess of 100 kg. Manufacturers have begun to produce wheelchairs for obese individuals, and testing may need to be performed with dummies up to 250 kg, though the greatest need is for one of 150 kg. The 7176-11 is not designed to be biomimetic (5). Its primary purpose is to act as a strength and stability dummy with mass distribution and center of mass (CoM) characteristics that present a reasonable facsimile of a person of the same mass.

Modifications to this design, the Hybrid II and Hybrid III motor vehicle crash test dummies, have been used to test the stability of wheelchairs (6,7). However, neither was manufactured in sizes greater than 100 kg. There has also been substantial discussion about the suitability of the Hybrid dummies for wheelchair fatigue testing. Cooper et al.

This project is based upon work supported by the Eastern Paralyzed Veterans of America, and the Paralyzed Veterans of America.

Address all correspondence to: Rory A. Cooper, PhD, Human Engineering Research Laboratories (151-R1), VA Pittsburgh Health Care System, 7180 Highland Drive, Pittsburgh, PA 15206; email: rcooper+@pitt.edu

have reported on modifications to the 7176-11 dummy to accommodate ultra-light wheelchairs, stand-up wheelchairs, and to provide more realistic fatigue loading (3,8). The proposed changes did not address altering the dummy for the added mass required to accommodate obese or very large individuals. The purpose of this study was to develop a means for modifying the design of the ISO 7176-11 test dummy to be suitable for testing with higher mass. We applied the following design criteria:

1. The current 100 kg ISO 7176-11 dummy would remain as the frame for the added mass;
2. The mass distribution of the modified dummy would be similar to that of an obese individual;
3. The CoM of the modified dummy segments would be representative of those of an obese individual;
4. The design could accommodate masses over 100 kg and provide specific guidelines for a 150 kg wheelchair test dummy.

METHODS

The current ISO 7176-11 dummies are based upon mass distribution and CoMs simplified from human anthropometric data for nonobese individuals (5), representing a 95th percentile person as three simple components: torso, upper legs, and lower legs/feet (see **Figure 1**). The torso (arms, head, neck, and trunk) has a mass of 61±3 kg. The upper legs are 31 ±3 kg, and the lower legs/feet are 7±1 kg. The total mass must be 100 kg +5/-2 kg.

Design modifications were determined using the following methods:

1. Determine from the anthropometry literature the distribution of mass and/or additional mass for obese individuals;
2. Determine the CoM for each segment based upon an obese individual;
3. Base the design dimensions on total mass only so that various dummy sizes can be chosen;
4. Convert data based upon anthropometric contours to simple geometric shapes for use with the ISO 7176-11.

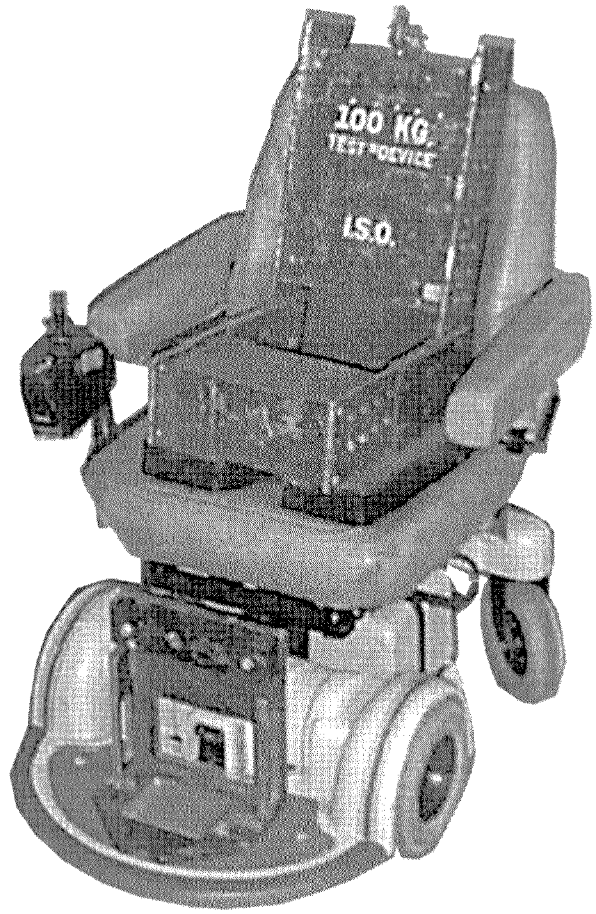

Figure 1.
Photograph of 100 kg ISO wheelchair test dummy.

Mass Distribution for Obese Wheelchair Test Dummies

As a person becomes obese, the additional mass does not become distributed evenly throughout the body, and its change in distribution alters the CoM of body segments. In our case, we were only interested in changes that affect the torso, upper legs, and lower legs/feet. The additional mass of obesity tends to concentrate in the lower torso (abdomen) and upper legs (thighs). Obesity is defined as the mass above the published norms based upon height and weight, and that mass has been reported to be distributed between the lower torso and the upper legs at a ratio of six to one (9-12). This means that a 150-kg obese person with a target weight of 100 kg has an additional 41.6 kg in the abdomen and 8.4 kg in the upper legs. We used this ratio as the basis for mass distribution in our design, assuming that changes in mass of other test dummy components are negligible.

Based upon Hanavan's (13,14) and Clauser's (15) data, we developed equations for the mass distribution for an obese dummy.

The mass of the head and neck:

$$M_{head} = 0.079M_{100kg} \quad (kg) \quad [1]$$

where

M_{100kg} = the total mass of the 100kg test dummy.

The mass of the head, neck, arms, and trunk combined for nonobese individuals:

$$M_{phant} = 0.47+14kg \quad [2]$$

M = the total mass of the desired test dummy

In order to design a dummy suitable for testing with a mass greater than 100 kg, we need to have an equation for the mass of the head, neck, arms, and trunk for obese individuals. If we assume that 5/6 of the additional mass goes into the lower torso, then Equation 2 leads to Equation 3.

$$M_{HANTobese} = 0.47(100) = 5/6(M - 100) = 14 \text{ (kg)} \quad [3]$$

$$= 0.83M - 22.3$$

Using Equation 3, the mass of the dummy torso for a 150 kg dummy would be 102.2 kg, as compared to 61 kg for a 100 kg dummy.

Based upon Hanavan's (13,14) and Clauser's (15) data, the mass of the upper torso can be determined using Equation 4.

$$M_{upper\text{-}torso} = 0.216M \quad (kg) \quad [4]$$

Assuming that the mass contributing to obesity is applied only to the lower torso and upper legs, then the upper-torso mass remains constant at 21.6 kg for dummies with mass in excess of 100 kg.

Based upon Equations 1-4, we can estimate the lower torso mass of the test dummy using Equation 5.

$$M_{lower\text{-}upper\_obese} = (0.83M - 22.3) - 7.9 - 21.6 \text{ (kg)}$$

$$= 0.83M - 51.8 \quad (kg) \quad [5]$$

Using the assumption that the change in mass in the lower legs/feet is negligible for the test dummy as the total mass increases, the mass of the upper legs can be determined using Equation 6.

$$M_{upper\text{-}legs\_obese} = 0.17M + 14 \quad (kg) \quad [6]$$

The mass of the upper legs for a 150 kg obese dummy would be 39.5 kg, compared to 31 kg for the 100 kg dummy. Equations 1-6 provide some guidance as to how mass is to be applied to the 100 kg ISO 7176-11 wheelchair test dummy to accommodate additional weights to simulate obese individuals.

Center of Mass for Obese Wheelchair Test Dummies

The CoM of the dummy is dependent upon the mass of the components, the shape of the components, and the location of the components with respect to one another. The height of a 100 kg, 95th percentile person is approximately 188 cm (16). Given these data, the CoM of the dummy components can be estimated using Hanavan's (13,14) models and data, as well as the data given in Winters (17).

The seated height of a 100 kg person 188 cm tall is about 97.8 cm (17). The CoM for a 100 kg person in relation to the seat for the head, upper torso, and lower torso are 85.5 cm, 53.4, and 22.1 cm, respectively (13,14,17). The CoM for the obese dummy with mass in excess of 100 kg can be described by Equation 7.

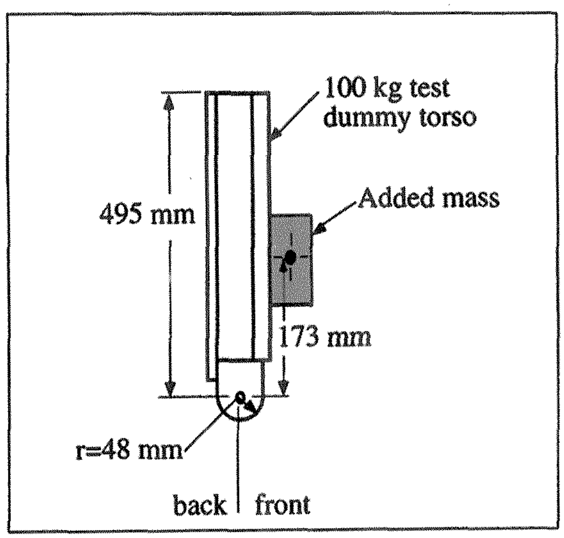

Figure 2.
Schematic showing vertical location of added mass for 150 kg wheelchair test dummy.

$$M_{HANTobese}y_{HANT} = M_{head}y_{head} + M_{upper\text{-}torso}y_{upper\text{-}torso} + M_{lower\text{-}torso\_obese}y_{lower\text{-}torso}$$

$$y_{HANT} = (M_{head}y_{head} + M_{upper\text{-}torso}y_{upper\text{-}torso} + M_{lower\text{-}torso\_obese}y_{lower\text{-}torso)} / M_{HANTobese}$$

$$y_{HANT} = \frac{(7.9)(85.4) + (21.6)(53.4) + (0.83M - 51.8)(22.09)}{(0.83M - 22.3)}$$

$$y_{HANT} = \frac{(22.1M + 823)}{(M - 26.9)} \quad \text{(cm)} \qquad [7]$$

If the desired dummy mass is 150 kg, then the height of the seated CoM for the torso from the seatbase should be 33.6 cm. For the 100 kg ISO 7176-11 test dummy, the CoM of the entire torso with the added material should be located 28.8 cm above the backrest pivot. This can be accomplished by placing the added lower-torso mass centered around 22.1 cm from the base or 17.3 cm from the dummy torso pivot point, see **Figure 2.**

To determine the x (i.e., horizontal) location of the CoM for the added mass, some additional modeling was required. We assumed that only the location of the CoM for the lower torso changes as an individual becomes obese. Therefore, the CoMs for components not affected by the lower torso go unchanged from those published in ISO 7176-11 (5). The CoM for the torso, however, does change. Equation 7 gives the y (vertical) location for the CoM. To determine the x-location of the CoM for the added mass (i.e., material), we assumed that the lower torso of a 100 kg person could be modeled as a cylinder; as the person becomes obese, this cylinder increases in diameter. Both the original cylinder and the enlarged one share a common intersection at the spine, see **Figure 3.** We are interested in the CoM for the additional material for the lower torso in order to achieve an equivalent dummy with mass greater than 100 kg. The CoM using this cylindrical model for the additional lower torso mass is given by Equation 8.

$$\chi_{added} = \frac{RM_R - rM_r}{= M_R - M_r} = \frac{RM_r - rM_r}{{}^5/_6(M_r - 100)} \quad \text{(cm)} \qquad [8]$$

M_R = Mass of the dummy lower torso plus the aded mass.
M_r = Mass of the lower torso of the 100 kg test dummy.
R = Radius of a circle representing the waist of an obese individual with a mass greater than 100 kg.
r = Radius of a circle representing the waist of a 100 kg individual.

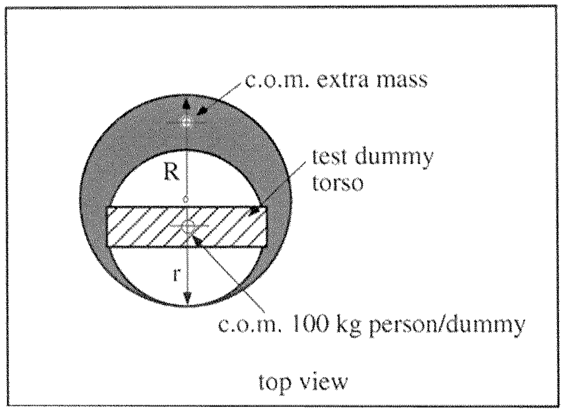

Figure 3.
Cylindrical model for torso masses.

To determine the mass of the lower torso of the 100 kg dummy, we used the dimensions of the torso, the mass of the torso, and the location of the CoM of the torso given in the ISO standard.

$$M_{dummy\_lower\text{-}torso} = M_{dummy\_torso} - \frac{y_{com\_torso}\, M_{dummy\_lower}}{l_{torso}} \quad \text{(kg)} \qquad [9]$$

$$M_{dummy\_lower\text{-}torso} = 61 - \frac{198}{495}61 = 36.6 \qquad \text{(kg)}$$

The additional lower-torso mass for obese dummies can be derived from Equations 8 and 9.

$$M_R = {}^5/_6\,(M - 100) + M = {}^5/_6(M - 100) + 36.6 \text{ (kg)}$$

$$M_R = 0.83M - 46.7 \qquad \text{(kg)} \qquad [10]$$

In order to determine the CoM, we needed to determine a means of estimating the waist radii for the equivalent circles. Several studies have shown waist circumference to be highly correlated with total body mass and obesity for a given height (10,11,18-

Table 1.
Equivalent radius and total body mass data from obese populations.

Equivalent radius (cm)	Total body mass (kg)	Study
18.3	100	Ross et al., 1994
18.4	98.6	Ross et al., 1993
16.2	90.0	Seidell et al., 1985
13.1	68.6	Klipstein-Grobusch et al., 1997

20). Based upon the mean waist circumference data presented for each of these studies on obese people, we developed a regression model relating equivalent radius to body mass (see **Table 1**). The equivalent radius was calculated by dividing the measured waist circumference by 2π.

$$r_{equivalent} = (\text{waist circumferenc}) / 2\pi \quad (\text{cm}) \quad [11]$$

Based upon the data presented in **Table 1,** a linear regression Equation was determined to relate equivalent radius to total body mass for obese individuals.

$$r_{equivalent} = 0.17M + 1.32 \quad (\text{cm}) \quad [12]$$

We found a Pearson product correlation coefficient of 0.992 and probability of error of p=0.008 for Equation (12). We chose to use r=18.3 cm for the equivalent radius for the 100 kg dummy. Based upon Equation 12, a 150 kg obese dummy would have an equivalent radius of 26.8 cm. Equations 8-12 can be combined to yield an equation for the x-location of the CoM of the additional material for the lower torso.

$$\chi_{added} = \frac{(0.17M + 1.32)[{}^{5}/_{6}(M - 100) + 36.6] - 18.3(36.6)}{{}^{5}/_{6}(M - 100)} \quad (\text{cm})$$

$$\chi_{added} = \frac{0.14M^2 - 6.8M - 731.4}{{}^{5}/_{6}(M - 100)} \quad (\text{cm}) \quad [13]$$

In order to determine the location of the CoM of the added material, we needed to make a simple translation of the data presented in Equation 13. Based upon our circular model, **Figure 3,** x_{added} is referenced to the spine. However, the 100 kg dummy torso is a rectangular box with its x CoM at the same location as the CoM of the equivalent cylinder (r) for a 100 kg person. Therefore, we must shift the CoM for the added material by r in order to reference it to the CoM for a 100 kg ISO wheelchair test dummy.

$$\chi_{COMadded} = \frac{0.14M^2 - 6.8M - 731.4}{{}^{5}/_{6}(M - 100)} - 18.3 \ (\text{cm}) \quad [14]$$

The equations presented in this section provide a basis for designing obese wheelchair test dummies.

DISCUSSION

Wheelchair test dummies are at the core of many of the ISO test methods. The test dummies act to load the chair for all of the strength and stability tests. Working Group One is responsible for the development of test methods for wheelchairs. This working group has received requests for the development of an ISO dummy that can be used for testing when a mass in excess of 100 kg is desired (4). Currently, there is no accepted means of modifying the dummy. Furthermore, we are unaware of any published reports that address this issue.

Working Group One has suggested that the best solution may be to modify the 100 kg test dummy to accommodate additional mass (4). This paper provides a description of how the mass could be added to the 100 kg ISO 7176-11 dummy to simulate an obese individual. Test laboratories have considerable resources invested in their current inventory of test dummies. The addition of another test dummy may not be welcome, especially since it is likely that the obese test dummy will be used infrequently. Nevertheless, the design of a wheelchair test dummy

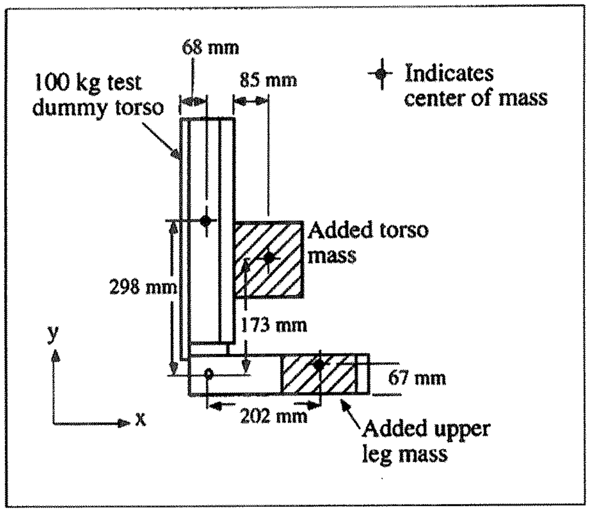

Figure 4.
Schematic showing location of added masses for 150 kg wheelchair test dummy.

that can accommodate masses in excess of 100 kg is important.

Test laboratories are likely to welcome a simple modification to the current 100 kg ISO 7176-11 test dummy. This can be accomplished by adding mass at appropriate locations. What is of interest to test laboratories is where the added mass needs to be placed. Based upon our design calculations, the CoM for the additional torso material (41.2 kg) for a 150 kg obese dummy should be 22.1 cm above the pivot of an ISO 7176-11 test dummy and 8.5 cm forward of the front edge of its torso. The additional upper-leg mass (8.8 kg) should be evenly distributed so as not to change the CoM for this segment. The changes to convert a 100 kg ISO dummy to an obese dummy with greater mass are illustrated in **Figure 4.**

Neither the ISO 7176-11 test dummy nor our modifications account for the inertial components of the body (5). Both designs only concern themselves with mass and CoM. Moreover, wheelchair test dummies are commonly made of steel, aluminum, and plywood. This makes them considerably stiffer than humans. The intent of the wheelchair test dummy design is not to be biomimetic, but to provide worst-case loading for strength and stability tests. Based upon these criteria, the modifications described herein are congruent with the spirit of ISO 7176-11.

A potentially significant shortcoming of the proposed design modification is that the torso may not remain stable. As mass is added to the torso, the CoM will move forward. With sufficient mass, the torso CoM will lie forward of the torso pivot. In most wheelchairs, the torso is reclined, which moves the CoM aft of the pivot. Therefore, the point of neutral stability will depend upon the wheelchair and the added mass of the dummy. The testing set-up procedure could be modified to have the test dummy positioned at the point of neutral stability or in a more stable position. During fatigue testing, the chair and dummy are subjected to dynamic loads that may cause the dummy to have a tendency to fall forward. However, the dummy torso is elastically restrained to the backrest during fatigue testing. Future research should determine whether there is a need for modification to the restraint during fatigue testing with obese test dummies.

Unfortunately, there remains a paucity of anthropometric data on individuals with disability. The lack of such data limited the design of the ISO 7176-11 test dummy and continues to be a limitation for this design study. Studies on the anthropometry of people with disabilities need to be conducted to support future designs of wheelchair test dummies.

ACKNOWLEDGMENTS

The authors would like to thank the members of the working groups of Technical Committee 173, Subcommittee 1 of the International Organization for Standardization (ISO), for their assistance in conducting this research. The authors would also like to thank Paula Stankovic for her assistance.

REFERENCES

1. Cooper RA. Rehabilitation engineering applied to mobility and manipulation. Bristol, UK: Institute of Physics Publishing; 1995.
2. Cooper RA, Gonzalez J, Lawrence B, Rentschler A, Boninger ML, VanSickle D. Performance of selected lightweight wheelchairs on ANSI/RESNA tests. Arch Phys Med Rehabil 1997;78:1138-44.
3. Cooper RA, Robertson RN, Lawrence B, et al. Life-cycle analysis of depot versus rehabilitation manual wheelchairs. J Rehabil Res Dev 1996;33:45-55.
4. Bardsley G. Draft minutes: test methods for wheelchairs. International Organization for Standards (ISO TC173 SC1 WG1-774); 1997.
5. International Organization for Standards. International standard, wheelchairs—part 11: test dummies. ISO 7176-11:1992(E), WG1-776; 1992.
6. Kirby RL. Wheelchair stability: important, measurable and modifiable. Technol Disabil 1996;5:75-80.

7. Nahum AM, Melvin JW. Accidental injury: biomechanics and prevention. New York: Springer-Verlag; 1993.
8. Cooper RA, Ster JF, Myren C, Petit DJ. An improved design of a 100 kilogram ISO/RESNA wheelchair test dummy. Proceedings of RESNA International '92; 1992 Jun 7-10; Toronto, ON, Canada. Washington, DC: RESNA Press; 1992. p. 210-2.
9. Barrows K, Snook JT. Effect of a high-protein, very-low-calorie diet on body composition and anthropometric parameters of obese middle-aged women. Am J Clin Nutr 1987;45:381-90.
10. Ross R, Shaw KD, Rissanen J, Martel Y, de Guise J, Avruch L. Sex differences in lean and adipose tissue distribution by magnetic resonance imaging: anthropometric relationships. Am J Clin Nutr 1994;59:1277-85.
11. Ross R, Shaw KD, Martel Y, de Guise J, Avuch L. Adipose tissue distribution measured by magnetic resonance imaging in obese women. Am J Clin Nutr 1993;57:470-5.
12. Schreiner PJ, Terry JG, Evans GW, Hinson WH, Crouse III JR, Heiss G. Sex-specific associations of magnetic resonance imaging-derived intra-abdominal and subcutaneous fat areas with conventional anthropometric indices. Am J Epidemiol 1996;144(4):335-45.
13. Hanavan EP. A mathematical model of the human body. Wright-Patterson Air Force Base, OH (AMRL-TR-64-102); 1964.
14. Hanavan EP. A personalized mathematical model of the human body. J Spacecraft 1996;3:446-8.
15. Clauser CE, McConville JT, Young JW. Weight, volume, and center of mass of segments of the human body. Wright-Patterson Air Force Base, OH (AMRL-TR-69-70); 1969.
16. Frisancho AR. New standards of weight and body composition by frame size and height for assessment of nutritional status of adults and the elderly. Am J Nutr 1984;40:808-19.
17. Winter DA, Biomechanics and motor control of human movement. 2nd ed. New York: John Wiley & Sons, Inc.; 1990.
18. Cisar CJ, Housh TJ, Johnson GO, Thorland WG, Hughes RA. Validity of anthropometric equations for determination of changes in body composition in adult males during training. J Sports Med Phys Fitness 1989;29:141-8.
19. Klipstein-Grobusch K, Georg T, Boeing H. Interviewer variability in anthropometric measurements and estimates of body composition. Int J Epidemiol 1997;26(1):S174-80.
20. Seidell JC, Bakx JC, De Boer E, Deurenberg P, Hautvast JGAJ. Fat distribution of overweight person in relation to morbidity and subjective health. Int J Obes 1985;9:363-74.

Submitted for publication October 29, 1997. Accepted in revised form January 8, 1998.