AN ABSTRACT OF THE DISSERTATION OF

Stamatis Agiovlasitis for the degree of Doctor of Philosophy in Exercise and Sport Science presented on August 15, 2007.

Title: Three-dimensional Motion of the Center of Mass and Energetic Cost Across a Variety of Walking Speeds: A Comparison Between Adults With and Without Down Syndrome.

Abstract approved:

_____

Jeffrey A. McCubbin

It has been previously suggested that the walking pattern of individuals with Down syndrome is inefficient. This is thought to result from increased instability, particularly in the medio-lateral direction, due to the characteristic joint laxity and muscle hypotonia of individuals with DS. Therefore, this work was an attempt to gain insight into the efficiency of gait in adults with DS by studying their mechanical and metabolic characteristics during treadmill walking. The first study examined the three-dimensional motion of the center of mass (COM) and the spatio-temporal characteristics of adults with and without DS at a variety of walking speeds. Fifteen adults with DS and 15 adults without DS walked on a treadmill at six and seven randomly presented dimensionless speeds (Froude numbers), respectively, during which kinematic data were collected. The range of medio-lateral COM position was greater in participants with DS, but the ranges of vertical COM position and anterior-posterior COM velocity did not differ between the groups. Participants with DS walked with faster steps across all speeds. Their step length was shorter only during

slow walking and their step width did not differ from adults without DS. Participants with DS were more variable in medio-lateral and vertical COM position, anterior-posterior COM velocity, and in all spatio-temporal parameters than their controls. The second study examined whether the net VO_2 and the net VO_2 per unit distance across the same walking speeds are different between adults with and without DS. The study also examined the relationship between the energetically optimal walking speed (EOWS) and the preferred walking speed (PWS) in both populations. Respiratory gases were collected from 14 adults with DS and 15 adults without DS as they walked at the same Froude numbers as for the first study. Adults with DS showed a higher net VO_2 and net VO_2 per unit distance, and a slower EOWS compared to adults without DS. The PWS was the same for both groups and did not appear to minimize the net VO_2 per unit distance in adults with DS. It was collectively concluded that the gait of adults with DS possesses several characteristics of inefficiency and has increased energetic requirements. Adults with DS do not prefer to walk at speeds that minimize the metabolic demand.

Three-dimensional Motion of the Center of Mass and Energetic Cost Across a Variety of Walking Speeds: A Comparison Between Adults With and Without Down Syndrome

by
Stamatis Agiovlasitis

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented August 15, 2007
Commencement June 2008

Doctor of Philosophy dissertation of Stamatis Agiovlasitis presented on August 15, 2007.

APPROVED:

Major Professor, representing Exercise and Sport Science

Chair of the Department of Nutrition and Exercise Sciences

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Stamatis Agiovlasitis, Author

ACKNOWLEDGEMENTS

This work would not have been made possible without the enthusiastic contribution of all participants. In particular, the adults with Down syndrome and their parents or caregivers were a source of encouragement and inspiration. Financial support was provided by Special Olympics International *(Special Olympics Healthy Athletes Health Professions Student Grant)* and by funds made available through the College of Health and Human Sciences. Karin Frederick, executive director of the Arc of Benton County, Jasper Smith, manager of the Benton County Developmental Disabilities Program, and Dave Zaback, executive director of Home Life facilitated participant recruitment and supported the student grant proposal to Special Olympics International. Ruben Guzman, Morgan O'Connor, and Matthew Boisselle, all exceptional undergraduate students, assisted with the lengthy data collection. Dr. William D. McArdle's enthusiasm as a researcher and educator are qualities that the present author reflected on in deciding to pursue a doctorate degree. Many thanks to Oregon State University. Its department of Nutrition and Exercise Sciences provides outstanding opportunities for graduate study. The Movement Studies in Disability program, in particular, embeds in its graduate students the academic curiosity, independence, and self-confidence required from future researchers in exploring important issues for individuals with disabilities. This is the outcome of the unique personal qualities of its director, Jeff McCubbin.

CONTRIBUTION OF AUTHORS

Stamatis Agiovlasitis conceptualized and designed this study, recruited all participants, attracted financial support, collected and processed the data, and conducted all analyses presented.

Dr. Jeffrey A. McCubbin supervised the conceptualization, design, and analysis of all work included here at its various stages. Furthermore, he facilitated participant recruitment, provided additional financial support, and offered editorial comments and suggestions on the interpretation of the findings.

Dr. Michael J. Pavol, Dr. Jeffrey Widrick, and Dr. Joonkoo Yun provided guidance in different aspects of study design, data analysis, and interpretation of the findings. Dr. Pavol also developed the MatLab programs required for the processing of the kinematic data.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

Στην Κ.

Chapter 1. Introduction

Introduction

Approximately 0.92 per 1,000 births result in newborns with the genetic abnormality known as Down syndrome (DS) that is produced by the presence of an additional chromosome 21 in their cells (Roizen, 2002). The numerous medical complications of DS include congenital heart defects, hematologic disorders, endocrine abnormalities, gastrointestinal malformations, orthopedic problems, sensory impairments, skin conditions, dental problems, epilepsy, cognitive limitations, and psychiatric disorders that may impact the quality of life of individuals with DS (American Academy of Pediatrics, 2001; Roizen, 2002). Despite the multitude of these conditions, advances in early medical interventions have enabled individuals with DS to live longer and reach late adulthood, in contrast to previous decades (Yang, Rasmussen, & Friedman, 2002). However, persons with DS are still considered at risk of preventable mortality and morbidity because they experience disparities in health care, including fewer opportunities for physical activity and exercise (Melville, Cooper, McGrother, Thorp, & Collacott, 2005; Stanish, Temple, & Frey, 2006; Sutherland, Couch, & Iacono, 2002; U.S. Department of Health and Human Services, 2002). Health promotion programs that incorporate health education and/or exercise have been proven successful in improving the health-related physical fitness of adults with DS and their attitudes towards exercise (Guerra Balic, Cuadrado Mateos, Geronimo Blasco, & Fernhall, 2000; Heller, Hsieh, & Rimmer, 2004; Tsimaras, Giagazoglou, Fotiadou, Christoulas, & Angelopoulou, 2003; Rimmer, Heller, Wang, & Valerio, 2004). However, even though walking habits play a central role in current health promotion strategies for persons with and without disabilities, the gait pattern of adults with DS has received little experimental attention (Pate et al., 1995; U.S. Department of Health and Human Services, 2000).

Of particular interest is the suggestion that the gait of individuals with Down syndrome (DS) may be less efficient than that of individuals without DS (Cioni, Cocilovo, Rossi, Paci, & Valle, 2001; Parker & Bronks, 1980; Parker, Bronks, & Snyder, 1986; Ulrich, Haehl, Buzzi, Kubo, & Holt, 2004). Specifically, the increased joint laxity, muscle hypotonia, cerebellum abnormalities, and cognitive limitations of individuals with DS are hypothesized to predispose these individuals to an unstable

and thus energetically demanding walking pattern (American Academy of Pediatrics, 1995, 2001; Buzzi & Ulrich, 2004; Cioni et al., 2001; Kubo & Ulrich, 2006a; Latash, 2000; Roizen, 2002). Notably, two of the reported barriers to exercising by adults with DS are exercise being 'too difficult' and 'lack of energy' (Heller et al., 2004) which may be experiential expressions of an inefficient gait pattern.

Efficiency reflects the contrast between energy output and energy input when performing movements (McArdle, Katch, & Katch, 2007). When considering the definition of efficiency, one needs to differentiate between *muscle efficiency* and *motor efficiency*. *Muscle efficiency* is the percent of energy available in foodstuffs that is converted to muscular work (Whipp & Wasserman, 1969). It is the product of *phosphorylation coupling efficiency* and *contraction coupling efficiency*, and it is considered to be about 29% (Cavanagh & Kram, 1985; Whipp & Wasserman, 1969). Put simply, the energy available in macronutrients can theoretically be converted to tension with a muscle efficiency of 29%. *Motor efficiency*, on the other hand, reflects the degree to which muscular forces act in the optimal direction of movement, and it is considered an essential element in the definition of skilled performance (Cavanagh & Kram, 1985; Sparrow, 1983; Sparrow & Newell, 1998; Whipp & Wasserman, 1969). Physiological data regarding the efficiency of walking in persons with DS are lacking and it is, therefore, difficult to conclude whether their *muscle efficiency* during walking is affected. However, previously reported findings suggest that *motor efficiency* may be reduced in individuals with DS (Buzzi & Ulrich, 2004; Cioni et al., 2001; Kubo & Ulrich, 2006a; Latash, 2000).

Among the characteristics of individuals with DS that are suggestive of decreased skill and motor efficiency are slower and more variable reaction times, reduced and more variable movement performance, and a general preference for slow movements (Baumeister & Kellas, 1968; Bruininks, 1974; Dobbins & Rarick, 1977; Hoover & Wade, 1985; Latash, 1993, 2000; Newell, 1985, 1997; Rarick, 1973; Wade, Newell, & Wallace, 1978). In addition, the documented co-contraction of antagonistic muscle groups during single-joint movements in individuals with DS may cause mechanical inefficiency (Aruin, Almeida, & Latash, 1996; Latash, Almeida, & Corcos, 1993; Winter, 2005). Longer reaction times, slow movements, and co-

contractions are thought to result from the inherent need of persons with DS to favor safety and accuracy in their movements at the expense of efficiency (Latash, 2000).

In the context of gait, previous research, primarily in children with DS, is suggestive of inefficiency. It has been proposed that individuals with DS co-contract their muscles during gait, as during single-joint movements, in order to cope with their instability due to joint laxity and muscle hypotonia, but at an energetic expense (Latash, 2000; Ulrich et al, 2004). In addition, the increased movement variability of persons with DS, also found in their gait kinematics (Cioni et al., 2001; Parker & Bronks, 1980; Ulrich et al., 2004), can affect the efficiency of forward progression. Inefficient gait may also result from greater medio-lateral motions as manifested by the wide steps and by the augmented side-to-side motions of the center of mass (COM) shown in children with DS, but not studied in adults with DS to date (Buzzi & Ulrich, 2004; Donelan, Kram, & Kuo, 2001; Kubo & Ulrich, 2006a, 2006b; Ulrich et al, 2004).

Because, during level walking, the body does not produce any external work and efficiency is difficult to calculate, the study of the three-dimensional COM motion and of spatio-temporal parameters can provide insight into gait efficiency in adults with DS. During gait, the COM has been theorized to follow a smooth sinusoidal pathway with minimal vertical and medio-lateral displacements resulting in the lowest possible energy cost (Saunders, Inman, & Eberhart, 1953). As in children with DS (Buzzi & Ulrich, 2004; Kubo & Ulrich, 2006a), the gait of adults with DS may also be characterized by increased instability, pronounced medio-lateral motion and, therefore, by an increased energy requirement to redirect the COM within a safe margin. A more variable COM motion, which may also signify an inefficient forward progression, could be expected by adults with DS who, as previously mentioned, show more variable movements (Latash, 2000). Furthermore, lateral stabilization of the body requires active control by higher centers, manifested in the amount of step width variability that is positively related to the metabolic cost (Bauby & Kuo, 2000; Donelan, Shipman, Kram, & Kuo, 2004; Kuo, 1999). Therefore, the study of the spatio-temporal characteristics may further improve the understanding of the energetic demands associated with walking in adults with DS.

A second approach to gaining insight into the efficiency of walking in persons with DS is by studying their *movement economy*, defined as the relative oxygen uptake (ml/kg/min) at a given workload or velocity under steady-rate conditions (McArdle et al., 2007). *Movement economy* is a more practical measure of the "ease of movement" that contributes substantially to endurance performance, although it is sensitive to differences in muscle and joint architecture between persons (Cavanagh & Kram, 1985; McArdle et al., 2007). In the presence of motor inefficiency, the walking economy of adults with DS may be adversely affected.

The relative oxygen uptake is further expressed per unit distance, often referred to as the *energy cost of transport*. It has been observed that this variable is a curvilinear function of velocity and that humans prefer to walk at a speed of about 1.2 m/s that is optimal in terms of energy cost of transport (Bhambhani & Singh, 1985; Margaria, 1976; Ralston, 1958). Although a mechanism through which humans sense their energetically optimal walking speed (EOWS) has not been identified empirically, it is thought that it resulted from evolutionary pressure and that it can be refined with practice (Alexander, 1989; Sparrow & Newell, 1998). If the gait of adults with DS has reduced efficiency, then the energy cost per unit distance across a variety of speeds may be greater than that of adults without DS. Furthermore, since individuals with DS have a preference for slow walking speeds, it is possible that this reflects an optimization of the energy cost of transport. Therefore, their EOWS may be slower, coinciding with a slower preferred walking speed (PWS), compared to adults without DS.

Collectively, the proposed gait inefficiency of adults with DS should be reflected in their three-dimensional COM motion, spatio-temporal parameters, economy, and energy cost per unit distance. Furthermore, the degree to which adults with DS choose to walk at speeds that are energetically optimal should be revealed in their PWS to EOWS relationship. Therefore, this study attempted to answer the following research questions.

1. Are the three-dimensional COM motions and the spatio-temporal variables of adults with DS during treadmill walking across a variety of speeds different or more variable compared to adults without DS?

2. Is walking economy at a variety of treadmill speeds reduced in adults with DS compared to adults without DS?
3. Is the energy cost per unit distance during treadmill walking across a variety of speeds greater in adults with than adults without DS?
4. Does the energy cost per unit distance to walking speed relationship of adults with DS demonstrate a slower EOWS than that of adults without DS?
5. Does the preferred walking speed (PWS) minimize the energy cost per unit distance in both populations?

Answers to these questions may lead to an appreciation of the energetic demand posed on adults with DS during walking and, therefore, to appropriately designed programs for health promotion.

References

Alexander, R.M. (1984). Walking and Running. *American Scientist, 72,* 1199-1227.

Alexander, R.M. (1989). Optimization and gaits in the locomotion of vertebrates. *Physiological Reviews, 69*(4), 1199-1227.

American Academy of Pediatrics, Committee on Sports Medicine and Physical Fitness, (1995). Atlantoaxial instability in Down syndrome: A subject review. *Pediatrics, 96*(1), 151-154.

American Academy of Pediatrics, Committee on Genetics, (2001). Health supervision of children with Down syndrome. *Pediatrics, 107*(2), 442-449.

Aruin, A.S., Almeida, G.L., & Latash, M.L. (1996). Organization of a simple two-joint synergy in individuals with Down syndrome. *American Journal of Mental Retardation, 101*(3), 256-268.

Baumeister, A.A., & Kellas, G. (1968). Reaction time and mental retardation. In N.R. Ellis (Ed.), *International review of research in mental retardation,* (vol. 2, pp. 163-192). New York: Academic Press.

Bauby, C.E., & Kuo, A.D. (2000). Active control of lateral balance in human walking. *Journal of Biomechanics, 33,* 1433-1440.

Bhambhani, Y., & Singh, M. (1985). Metabolic and cinematographic analysis of walking and running in men and women. *Medicine and Science in Sports and Exercise, 17*(1), 131-137.

Bruininks, R.H. (1974). Physical and motor development of retarded persons. In N.R. Ellis (Ed.) *International review of research in mental retardation*, (vol. 7, pp. 209-261). New York: Academic Press.

Buzzi, U.H., & Ulrich, B.D. (2004). Dynamic stability of gait cycles as a function of speed and system constraints. *Motor Control, 8,* 241-254.

Cavanagh, P.R., & Kram, R. (1985). The efficiency of human movement – a statement of the problem. *Medicine and Science in Sports and Exercise, 17*(3), 304-308.

Cioni, M., Cocilovo, A., Rossi, F., Paci, D., & Valle, M.S. (2001). Analysis of ankle kinetics during walking in individuals with Down syndrome. *American Journal of Mental Retardation, 106*(5), 470-478.

Dobbins, A.D., & Rarick, L.G. (1977). The performance of intellectually normal and educable mentally retarded boys on tests of throwing accuracy. *Journal of Motor Behavior, 9*(1), 23-28.

Donelan, J.M., Kram, R., Kuo, A.D. (2001). Mechanical and metabolic determinants of the preferred step width in human walking. *Proceedings of the Royal Society of London B, 268,* 1985-1992.

Donelan, J.M., Shipman, D.W., Kram, R., Kuo, A.D. (2004). Mechanical and metabolic requirements for active lateral stabilization in human walking. *Journal of Biomechanics, 37,* 827-835.

Farley, C.T., & Ferris, D.P. (1998). Biomechanics of walking and running: Center of mass movements to muscle action. In J.O. Holloszy (Ed.), *Exercise and Sports Science Reviews (Vol. 26, pp. 253-285).* Baltimore: Williams & Wilkins.

Guerra Balic, M., Cuadrado Mateos, E., Geronimo Blasco, C., & Fernhall, B. (2000). Physical fitness levels of physically active and sedentary adults with Down syndrome. *Adapted Physical Activity Quarterly, 17,* 310-321.

Heller, T., Hsieh, K., & Rimmer, J.H., (2004). Attitudinal and psychosocial outcomes of a fitness and health education program on adults with Down syndrome. *American Journal of Mental Retardation, 109*(2), 175-185.

Hoover, J.H., & Wade, M.G. (1985). Motor learning theory and mentally retarded individuals: a historical review. *Adapted Physical Activity Quarterly, 2,* 228-252.

Kubo, M., & Ulrich, B. (2006a). Coordination of the pelvis-HAT (head, arms and trunk) in anterior-posterior and medio-lateral directions during treadmill gait in preadolescents with/without Down syndrome. *Gait and Posture, 23,* 512-518.

Kubo, M., & Ulrich, B. (2006b). Early stage of walking: Development of control in medio-lateral and anteroposterior directions. *Journal of Motor Control, 38*(3), 229-237.

Kuo, A.D. (1999). Stabilization of lateral motion in passive dynamic walking. *International Journal of Robotics Research, 18,* 917-930.

Latash, M.L. (1993). *Control of human movement*. Champaign, IL: Human Kinetics.

Latash, M.L. (2000). Motor coordination in Down syndrome: The role of adaptive changes. In D.J. Weeks, R. Chua, & D. Elliott (Eds.), *Perceptual-motor behavior in Down syndrome (pp. 199-223).* Champaign, IL: Human Kinetics.

Latash, M.L., Almeida, G.L., & Corcos, D.M. (1993). Preprogrammed reactions in individuals with Down syndrome: The effects of instruction and predictability of the perturbation. *Archives of Physical Medicine and Rehabilitation, 74,* 391-399.

Mahan, K.T., Diamond, E., & Brown, D. (1983). Podiatric profile of the Down's syndrome individual. *Journal of the American Podiatry Association, 73*(4), 173-179.

Margaria, R. (1976). *Biomechanics and energetics of muscular exercise.* Oxford: Clarendon Press.

McArdle, W.D., Katch, F.I., & Katch, V.L. (2007). *Exercise physiology: Energy, nutrition, and human performance*. Baltimore: Lippincott Williams & Wilkins.

Melville, C.A., Cooper, S.-A., McGrother, C.W., Thorp, C.F., & Collacott, R. (2005). Obesity in adults with Down syndrome: A case control study. *Journal of Intellectual Disability Research, 49*(2), 125-133.

Newell, K.M. (1985). Motor skill acquisition and mental retardation: overview of traditional and current orientations. In J.E. Clark & J.H. Humphrey (Eds.), *Motor development: Current selected research* (pp. 183-192). Princeton, NJ: Princeton Books.

Newell, K.M. (1997). Motor skills and mental retardation. In W.E. MacLean, Jr. (Ed.), *Ellis' Handbook of mental deficiency: Psychological theory and research* (pp. 275-308). Mahwah, NJ: Erlbaum.

Parker, A.W., & Bronks, R. (1980). Gait of children with Down syndrome. *Archives of Physical Medicine and Rehabilitation, 61,* 345-351.

Pate, R.R., Pratt, M., Blair, S.N., Haskell, W.L., Macera, C.A., Bouchard, C., et al. (1995). Physical activity and public health. A recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. *JAMA, 273*(5), 402-407.

Ralston, H.J. (1958). Energy-speed relation and optimal speed during level walking. *Int. Z. angew. Physiol.*, 17, 277-288.

Rarick, G.L. (1973). Motor performance of mentally retarded children. In G.L. Rarick (Ed.), *Physical activity: Human growth and development* (pp. 225-256). New York: Academic Press.

Rimmer, J.H., & Yamaki, K. (2006). Obesity and intellectual disability. *Mental Retardation and Developmental Disabilities Research Reviews, 12,* 22-27.

Rimmer, J.H., Heller, T., Wang, E., & Valerio, I. (2004). Improvements in physical fitness in adults with Down syndrome. *American Journal of Mental Retardation, 109*(2), 165-174.

Roizen, N.J. (2002). Down syndrome. In M.L. Batshaw (Ed.), *Children with disabilities (pp. 307-320).* Baltimore: Paul H. Brooks.

Sparrow, W.A. (1983). The efficiency of skilled performance. *Journal of Motor Behavior, 15*(3), 237-261.

Sparrow, W.A., & Newell, K.M. (1998). Metabolic energy expenditure and the regulation of movement economy. *Psychonomic Bulletin & Review, 5*(2), 173-196.

Stanish, H.I., Temple, V.A., & Frey, G.C. (2006). Health-promoting physical activity of adults with mental retardation. *Mental Retardation and Developmental Disabilities Research Reviews, 12,* 13-21.

Sutherland, G., Couch, M.A., & Iacono, T. (2002). Health issues for adults with developmental disability. *Research in Developmental Disabilities, 23,* 422-445.

Tsimaras, V., Giagazoglou, P., Fotiadou, E., Christoulas, K., & Angelopoulou, N. (2003). Jog-walk training in cardiorespiratory fitness of adults with Down syndrome. *Perceptual and Motor Skills, 96,* 1239-1251.

Ulrich, B.D., Haehl, V., Buzzi, U.H., Kubo, M., & Holt, K.G. (2004). Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Human Movement Science, 23,* 133-156.

U.S. Department of Health and Human Services (2000). Healthy people 2010: Understanding and improving health. Washington, DC: U.S. Government Printing Office.

U.S. Department of Health and Human Services (2002). *Closing the gap: A national blueprint to improve the health of persons with mental retardation.* Report of the Surgeon General's Conference on Health Disparities and Mental Retardation. Retrieved January 2, 2007, from http://www.specialolympics.org.

Wade, M.G., Newell, K.M., & Wallace, S.A. (1978). Decision time and movement time as a function of response complexity in retarded persons. *American Journal of Mental Deficiency, 83*(2), 135-144.

Whipp, B.J., & Wasserman, K. (1969). Efficiency of muscular work. *Journal of Applied Physiology, 26*(5), 644-648.

Winter, D.A. (2005). Biomechanics and motor control of human movement. Hoboken, NJ: John Wiley & Sons.

Yang, Q., Rasmussen, S.A., & Friedman, J.M. (2002). Mortality associated with Down's syndrome in the USA from 1983 to 1997: A population based study. *Lancet, 359,* 1019-1025.

Chapter 2. Manuscript A

Three-dimensional motion of the center of mass across a variety of walking speeds in adults with and without Down syndrome

Stamatis Agiovlasitis, Michael J. Pavol, and Jeffrey A. McCubbin

Abstract

To gain insight into the efficiency of gait in adults with Down syndrome (DS), this study examined the three-dimensional motion of their center of mass (COM) and their spatio-temporal characteristics across a variety of walking speeds. Fifteen adults with DS and 15 adults without DS walked on a treadmill at six and seven randomly presented dimensionless speeds (Froude numbers), respectively, during which kinematic data were collected. The range of medio-lateral COM position was greater in participants with DS, but the ranges of vertical COM position and anterior-posterior COM velocity did not differ between the groups. Participants with DS walked with faster steps across all speeds. Their step length was shorter only during slow walking and their step width did not differ from adults without DS. Participants with DS were more variable in medio-lateral and vertical COM position, anterior-posterior COM velocity, and in all spatio-temporal parameters than their controls. It was concluded that the gait of adults with DS is unstable, particularly in the medio-lateral direction, and that it possess several characteristics of inefficiency.

(174 words)

Keywords: *disability, locomotion, instability, motor-control*

Among the unique characteristics of individuals with the genetic abnormality identified as Down syndrome (DS) are increased joint laxity, muscle hypotonia, cerebellum abnormalities, and cognitive limitations (American Academy of Pediatrics, 1995, 2001; Latash, 2000; Newell, 1997; Roizen, 2002). These characteristics are generally considered to create an unstable and, thus, inefficient gait pattern (Buzzi & Ulrich, 2004; Cioni, Cocilovo, Rossi, Paci, & Valle, 2001; Kubo & Ulrich, 2006a; Parker & Bronks, 1980; Parker, Bronks, & Snyder, 1986; Ulrich, Haehl, Buzzi, Kubo, & Holt, 2004). Although there is some empirical information regarding the gait of children with DS, little is known about the gait of adults with DS. An improved appreciation of the locomotor pattern of adults with DS who experience insufficient levels of health care, including fewer opportunities to participate in physical activity and sports compared to the general population, may facilitate the development of appropriate health promotion strategies for these individuals (U.S. Department of Health and Human Services, 2002).

Movement efficiency, which reflects the degree to which muscular forces act in the optimal direction during movement, may be affected during walking in persons with DS (Whipp & Wasserman, 1969). The previously documented co-activation of antagonistic muscle groups during single-joint movements of individuals with DS has also been suggested to be present in their gait as a strategy that can improve stability, but one that decreases efficiency (Aruin, Almeida, & Latash, 1996; Latash, Almeida, & Corcos, 1993; Latash, 2000; Ulrich et al, 2004; Winter, 2005). In addition, the efficiency of forward progression in persons with DS may be reduced by their more variable movements which have also been found in their gait kinematics (Cioni et al., 2001; Newell, 1997; Parker & Bronks, 1980; Sparrow & Day, 2002; Ulrich et al., 2004). Inefficient gait may also result from greater medio-lateral motions, as manifested by the wide steps and by the increased side-to-side motions of the upper-body center of mass (COM) shown in children with DS (Buzzi & Ulrich, 2004; Kubo & Ulrich, 2006a; Ulrich et al, 2004), but not documented in adults with DS to date.

In walking, the COM has been theorized to follow a smooth sinusoidal pathway with minimal vertical and medio-lateral displacements resulting in the lowest possible energy cost (Saunders, Inman, & Eberhart, 1953). In the sagittal plane,

walking has been modeled as an inverted pendulum that maximizes the passive recovery of gravitational to kinetic energy while minimizing the vertical excursion of the COM (Alexander, 1984; Farley & Ferris, 1998; Saunders et al., 1953). However, considerable energy is expended because walking involves alternating phases of braking and accelerating during the gait cycle (Alexander, 1984; Farley & Ferris, 1998). These fluctuations may thus be reflected in the change in anterior-posterior COM velocity. On the other hand, a pronounced medio-lateral COM motion during gait, generally considered a manifestation of instability, can increase the mechanical energy required to maintain balance (Chou, Kaufman, Hahn, & Brey, 2003; Kubo & Ulrich, 2006a). Furthermore, a more variable three-dimensional COM trajectory from stride to stride may contribute to a less consistent and, therefore, less efficient forward progression. The study of the three-dimensional COM motion may thus provide insight into the efficiency of walking in persons with DS.

Although anterior-posterior movement is largely a passive process, medio-lateral stabilization of the body requires active control by higher centers that causes a significant metabolic cost as step width and step width variability increase (Bauby & Kuo, 2000; Donelan, Kram, & Kuo, 2001; Donelan, Shipman, Kram, & Kuo, 2004; Kuo, 1999). Because individuals with DS appear to widen their steps to improve medio-lateral stability and because they may have greater step width variability due to their more variable kinematics, their gait may be energetically more demanding than that of individuals without DS (Kubo & Ulrich, 2006a; Parker & Bronks, 1980; Parker, Bronks, & Snyder, 1986; Ulrich et al., 2004). Therefore, an improved picture of walking efficiency in persons with DS may be generated by studying their spatio-temporal gait characteristics.

In summary, previous findings suggest that the gait of adults with DS may be less efficient than that of adults without this genetic syndrome. However, limited experimentation has been conducted to substantiate this claim. Therefore, this study attempted to provide evidence of inefficiency for the gait of adults with DS by evaluating the three-dimensional motion of their full-body COM and a set of spatio-temporal parameters at a variety of walking speeds in comparison to adults without DS. It was hypothesized that adults with DS will show increased and more variable

medio-lateral COM motion due to their instability, accompanied by augmented step width and step width variability. There was no specific hypothesis regarding mean differences in anterior-posterior COM and vertical COM motions. However, a more variable pattern in these variables was anticipated by adults with DS.

Method

Participants

Fifteen adults with DS (age range: 19-44 years) and 15 adults without DS and with no other disability (age range: 18-42 years) volunteered to participate in this study. The two groups of participants were matched for gender (8 males and 7 females) and did not differ in age and body mass. However, participants with DS had greater body mass index, and shorter stature and leg length than those without DS (Table 1). Participants with DS were recruited through community-based service programs for individuals with developmental disabilities. Their parents or direct caregivers indicated that these individuals had mild-to-moderate forms of intellectual disability (ID). Eight participants with DS lived with their parents, three resided in group homes, and four lived independently. Of the participants with DS, four had congenital heart defects corrected with surgery early in childhood and one had atlanto-axial instability but no restrictions to physical activity. Given these considerations, participants were in overall good health with no documented gait abnormalities as reported by them (non-DS group) or by their parent/direct caregiver (DS group). With the exception of one female with DS, participants were active and exercised regularly. Most participants with DS had part-time jobs requiring physical labor. All participants had some prior experience with the use of a treadmill, except for two females with DS. The above information was collected with a health history questionnaire completed by participants (non-DS group) or by their parent/direct caregiver (DS group) (Appendix B). Participants and their legal guardians (DS group) provided informed consent in accordance with regulations set by the Institutional Review Board.

Experimental Design and Procedures

Three laboratory sessions were conducted for participants without DS whereas four sessions were conducted for participants with DS. These sessions took place over a period of two to four consecutive weeks for each participant.

The first appointment for participants without DS and the first two appointments for participants with DS were devoted to familiarization with treadmill locomotion. First, the body mass, height, and leg length were measured. Leg length was defined as the height of the right greater trochanter from the floor during standing with shoes on and was measured using an anthropometer (GPM Anthropological Instruments, Zurich, Switzerland). This leg length was only used to calculate the walking speeds (Froude numbers) for each participant as described below. Then, participants with DS completed six bouts of treadmill walking, each lasting five minutes, at a Froude number of 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 whereas participants without DS walked for an additional five minutes at a Froude # of 0.7. The dimensionless Froude number ($F = v / \sqrt{gL}$, where **v** is traveling speed, **g** is the acceleration of gravity, and **L** is leg length) was used to normalize walking speed relative to leg length. Earlier work in our lab indicated that the Froude numbers used in this study represent a full range of walking speeds for persons with and without DS, respectively.

During the next session (second for adults without DS, but third for adults with DS), the energy cost of locomotion at the speeds described earlier was determined during a series of six-minute-long walking bouts using expired gas analysis. These data are not presented here. Overall, participants with and without DS had 96 and 77 minutes of practice time on the treadmill prior to data collection, respectively.

COM data were collected during the last appointment with a nine-camera motion capture system (Vicon, Oxford, UK). First, 35 reflective markers, 9 mm in diameter, were attached on participants using the Vicon Plug-in-Gait marker set. Following a static trial, participants walked on a treadmill (410, Biodex, Shirley, New York) at the same speeds as during the familiarization session(s). The walking trials were performed in a randomized order and they were separated by a three-minute resting period. Following four minutes of walking at each speed, data were collected for 30-35 steps at a frequency of 60 Hz. The session was concluded with a set of anthropometric measurements required in the Plug-in-Gait model and taken on the right side of the body: leg length, knee width, ankle width, shoe thickness, shoulder offset, elbow width, wrist width, and hand thickness.

Data Reduction and Analysis

Kinematic data were filtered with a fourth-order, no-lag Butterworth low-pass filter at a cut-off frequency of nine Hz, established with residual analysis (Winter, 2004). The three-dimensional position of the whole-body COM was determined, using the Vicon Plug-in-Gait software from a 15-segment model: two feet, two shanks, two thighs, two hands, two forearms, two upper-arms, pelvis, trunk, and head. The timing of heel-strike was identified from the anterior-posterior velocity profile of the heel markers using an autocorrelation procedure available in Workstation. This procedure, which was confirmed visually for every heel-strike within each trial, allowed for the determination of step time. Step length was calculated from step time and treadmill speed and was normalized to leg length. Step width was defined as the lateral distance between the heel markers from heel-strike to contra-lateral heel-strike.

Dependent variables analyzed statistically included the range of the medio-lateral COM position during the stride (R-COMy), the range of vertical COM position during the step (R-COMz) expressed as a function of body height, and the range of the anterior-posterior COM velocity relative to treadmill speed during the step (R-V-COMx) expressed as a Froude number. Ranges were averaged across all strides or steps recorded at a given speed. The root-mean-square (RMS) between-stride standard deviations of medio-lateral and vertical COM position (COMy and COMz, respectively) and of anterior-posterior COM velocity (V-COMx) across the stride were also analyzed as measures of variability. Between-stride standard deviations were determined at each 2% of stride, following cubic-spline interpolation of the data. Additional dependent variables included mean step width, step length, and step time, as well as the between-step standard deviation in these three spatio-temporal variables.

Differences between the DS and non-DS groups in each of the above dependent measures were analyzed with 2 x 6 (group by speed) ANOVA with repeated measures on the second factor. When the sphericity assumption was not met, the Greenhouse-Geisser adjustment was used. Simple follow-up ANOVA between groups at each speed with a Bonferroni-adjusted alpha level (0.008) were performed when warranted by a significant interaction effect. Differences between groups in the above dependent variables were also evaluated by effect sizes, estimated by partial eta

squared (η^2). The alpha level was set at 0.05. Statistical analysis was conducted using SPSS (version 15.0).

Results

The repeated-measures comparison for R-COMy yielded a significant main effect for group ($p < 0.05$, partial $\eta^2 = 0.13$) without an interaction, indicating that participants with DS walked with a greater range of the medio-lateral COM motion across all speeds. Furthermore, a significant main effect for speed ($p < 0.001$, partial $\eta^2 = 0.86$) showed that, for both groups, R-COMy decreased as speed increased. On the other hand, a significant interaction effect ($p < 0.001$), combined with the results of follow-up ANOVA at each speed revealed that adults with DS had a smaller R-COMz at Froude 0.6 and did not differ from adults without DS at the remaining speeds (Figure 1). Moreover, R-V-COMx did not differ between the groups as shown by non-significant main effects and interaction.

Participants with DS were more variable between strides in both medio-lateral and vertical COM position, as well as in anterior-posterior COM velocity, compared to their controls. The repeated-measures analysis for the RMS standard deviation of COMy across the stride demonstrated significant main effects for group and speed ($p < 0.05$, partial $\eta^2 = 0.15$ and 0.10, respectively) without an interaction. For the between-stride standard deviation in COMz and V-COMx, the same analysis showed significant interaction effects ($p \leq 0.001$) followed by significant univariate comparisons across all walking speeds (Table 2 and Figure 2).

The response to walking speed of mean step width, step length, and step time, as well as the response of between-stride variability in these measures, differed between the groups, as shown by significant speed-by-group interactions ($p < 0.05$). Univariate analyses at each speed level indicated that adults with DS walked with shorter step length only at Froude 0.1 and 0.2. Their step time, however, was significantly shorter at all speeds indicating higher cadence compared to adults without DS. Although step width did not differ between the groups at any of the speeds, step width was more variable in adults with DS across most speeds with the exception of Froude 0.1. Participants with DS were also more variable than participants without DS in step length and step time, but only at the faster speeds

(Froude 0.3 – 0.6 and Froude 0.4 – 0.6, respectively). The above results are further described in Tables 3 and 4.

Discussion

The inherent joint laxity and muscle hypotonia of individuals with DS have been suggested to create an unstable and inefficient gait pattern (Buzzi & Ulrich, 2004; Cioni et al, 2001; Kubo & Ulrich, 2006a; Ulrich et al., 2004). To gain insight into the stability and efficiency of gait in these persons this study examined the three-dimensional motion of their full-body COM. It was generally hypothesized that adults with DS would demonstrate a more pronounced and more variable COM motion than adults without DS, particularly in the medio-lateral direction. The study also hypothesized that, in response to their increased instability, adults with DS would show differences from their controls in a set of spatio-temporal measures.

The expectation that adults with DS would have greater medio-lateral motions of their COM as a manifestation of increased instability in the frontal plane was confirmed by the present results, extending to adults similar findings reported for children with DS (Kubo & Ulrich, 2006a). This greater medio-lateral COM sway of individuals with DS is most likely the outcome of their inherent joint laxity and muscle hypotonia as previously suggested (Buzzi & Ulrich, 2004; Ulrich et al., 2004).

Enhanced side-to-side motions, however, may increase the energetic demand to redirect the COM within a safe margin. The pattern of R-COMy and faster steps observed in participants with DS is suggestive of increased medio-lateral COM velocity and, therefore, greater COM acceleration in the frontal plane. Since COM acceleration is a reflection of ground reaction force (GRF) (Farley & Ferris, 1998; Hamill & Knutzen, 2003), it follows that the medio-lateral component of the GRF is more likely greater for adults with DS compared to adults without DS. Therefore, the abduction-adduction musculature of adults with DS likely produces greater medio-lateral forces in order to maintain stability thus increasing the metabolic requirement. Additional energetic costs may be caused by a greater demand for upper-body stabilization.

Less efficient movement in adults with DS is also suggested by their greater between-stride variability in medio-lateral COM position. This finding is possibly a

different manifestation of increased instability caused by joint laxity and muscle hypotonia and it is consistent with the previously reported increased kinematic variability of these persons (Parker & Bronks, 1980; Ulrich et al, 2004). Furthermore, increased variability in side-to-side COM motion may pose an additional computational demand on the central nervous system, which actively controls lateral balance during walking (Bauby & Kuo, 2000; Kuo, 1999). Active control processes, however, may be affected in adults with DS who possess neurological deficiencies, resulting in difficulty to control an inconsistent movement pattern (Latash, 2000; Sparrow & Day, 2002). Therefore, the loose joints, hypotonic muscles, and affected nervous system of individuals with DS may collectively produce a more variable and metabolically costly gait.

Step width did not differ between the groups in accordance with earlier work in toddlers with DS (Kubo & Ulrich, 2006b), but contrary to previously reported findings in children with DS (Kubo & Ulrich, 2006a; Ulrich et al, 2004). This discrepancy is possibly the outcome of differences in the operational definition of this variable across studies, as well as significant variability between participants for both groups in this study. However, although widening the step can potentially reduce the medio-lateral body motion, such strategy to improve stability may not have been preferred by participants with DS who employed essentially the same step width across all speeds.

On the other hand, step width variability was significantly higher in adults with DS than in adults without DS at all speeds except the slowest one. This finding is a reflection of an increased active control required for lateral stabilization (Bauby & Kuo, 2000; Donelan et al, 2004). Adults with DS may be varying their medio-lateral foot placement more than their controls in response to their more variable side-to-side body sway in order to prevent falls. Because this active strategy has been shown to have an energetic cost (Donelan et al, 2004), it follows that the locomotor pattern of individuals with DS may be uneconomical. In spite of this, the increased spatial variability of adults with DS appears to be a functional adaptation to instability and as such should not be the focus of corrective interventions (Latash & Anson, 1996).

In the sagittal plane, the average motion of the COM was roughly the same for both groups. However, adults with DS demonstrated a more variable pattern,

suggesting decreased efficiency of movement during forward progression. First, R-V-COMx did not differ between adults with and without DS across all walking speeds. In both groups of participants, forward COM velocity (V-COMx) increased during the loading response as the contra-lateral foot pushes the body forward. Thereafter, V-COMx rapidly decreased to reach a minimum at the end of mid-stance and then increased again as the body falls forward during terminal stance (Figure 2). Therefore, this normal pattern of successive accelerations and decelerations of COM during the gait cycle which is considered an inherent source of walking inefficiency (Alexander, 1984) was not more pronounced in adults with DS compared to their controls as reflected in R-V-COMx. However, between-stride variability of V-COMx was greater in the DS group across all speeds suggesting, an uneven forward progression that may be less efficient overall.

The normalized step length increased as a function of walking speed in both groups. At the two slowest speeds, adults with DS took shorter steps than adults without DS, but this difference did not persist for the remaining speeds. Notably, step length variability did not differ between the groups at the two slowest speeds indicating a similar control of this variable during slow walking. For the remaining speeds, however, participants with DS showed greater step length variability than participants without DS. This finding is suggestive of a more involved active control of anterior-posterior motion. Although this response is more likely an adaptation to the increased instability of adults with DS, it may further contribute to a less smooth forward progression pattern and to greater metabolic demand.

Adults with DS did not differ from adults without DS in their mean range of vertical COM position during the step (R-COMz) except at Froude 0.6. For both groups, R-COMz grew as speed increased, suggesting that both adults with and without DS make a similarly efficient use of the inverted pendulum character of walking (Alexander, 1984; Farley & Ferris, 1998). To achieve faster walking speeds and maximize the conversion of gravitational to kinetic energy, individuals with and without DS elongated their step with a stiff leg, thus increasing R-COMz (Alexander, 1984; Farley & Ferris, 1998; Ounpuu, 1994). Non-surprisingly, adults with DS showed greater COMz variability since their step length was also more variable. R-

COM-z reached a plateau in both groups of participants. This plateau, however, occurred at a slower speed for adults with DS causing their R-COMz at Froude 0.6 to be significantly smaller than that of adults without DS (Figure 1). The most likely means for the reduction in R-COMz is increased knee flexion in a more running-like gait pattern which can facilitate the storage and return of energy by elastic mechanisms (Alexander, 1984; Farley & Ferris, 1998; Ounpuu, 1994; Saunders et al., 1953). Therefore, it is possible that the gait of individuals with DS is so uneconomical that a switch to the energy saving characteristics of running may be warranted at slower speeds compared to individuals without disabilities.

The extent to which the above results using treadmill locomotion apply to over-ground walking for adults with DS is presently unknown. The measurement of V-COMx as presented here, in particular, assumes a constant treadmill speed. However, the belt speed typically varies somewhat. Nevertheless, the large number of strides included in the analysis may have accounted for this variation. Moreover, although the amount of treadmill walking familiarization was more than the recommended for persons without disabilities and most participants with DS had previously used a treadmill, the exact amount of familiarization required to produce a consistent pattern in persons with DS is presently unknown (Charteris & Taves, 1978; Schieb, 1986; Wall & Charteris, 1980, 1981). For this reason, two familiarization sessions were conducted for participants with DS. Another limitation relates to the applicability of the Plug-In-Gait model used to estimate COM motion which assumes similar anthropomorphy for both groups. However, the extent to which body proportions differ between adults with and without DS has not been explored.

In conclusion, adults with DS possess an unstable walking pattern, particularly in the medio-lateral direction, that is most likely the outcome of their inherent joint laxity and muscle hypotonia. Side-to-side COM motions were both greater and more variable across speeds in adults with DS compared to adults without DS. In contrast, the mean vertical COM motions and the mean anterior-posterior COM velocity were very similar between the groups, but with increased stride-to-stride variability in participants with DS. To accommodate their destabilizing COM motions adults with DS take faster steps than their controls and show greater variability in spatio-temporal

variables that should not be considered pathologic. Collectively, the above findings are suggestive of an uneconomical and potentially fatiguing gait pattern. Health promotion, physical education, recreation, and exercise training specialists should use this knowledge in designing effective programs for these individuals. For example, individuals with DS may be advised to use the treadmill side-bars in order to improve stability and increase compliance with a walking training program. Further research may also explore the potential benefits of lateral stabilization during early intervention walking programs designed to promote motor development in children with DS. More importantly, a better understanding of atypical gait patterns may improve our appreciation of the experience of movement in individuals with disabilities.

References

Alexander, R. M. (1984). Walking and running. *American Scientist, 72,* 1199-1227.

American Academy of Pediatrics, Committee on Sports Medicine and Physical Fitness (1995). Atlantoaxial instability in Down syndrome: A subject review. *Pediatrics, 96*(1), 151-154.

American Academy of Pediatrics, Committee on Genetics, (2001). Health supervision of children with Down syndrome. *Pediatrics, 107*(2), 442-449.

Bauby, C.E., & Kuo, A.D. (2000). Active control of lateral balance in human walking. *Journal of Biomechanics, 33,* 1433-1440.

Buzzi, U.H., & Ulrich, B.D. (2004). Dynamic stability of gait cycles as a function of speed and system constraints. *Motor Control, 8,* 241-254.

Charteris, J., & Taves, C. (1978). The process of habituation to treadmill walking: a kinematic analysis. *Perceptual and Motor Skills, 47,* 659-666.

Chou, L., Kaufman, K.R., Hahn, M.E., Brey, R.H. (2003). Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. *Gait and Posture, 18,* 125-133.

Cioni, M., Cocilovo, A., Rossi, F., Paci, D., & Valle, M.S. (2001). Analysis of ankle kinetics during walking in individuals with Down syndrome. *American Journal of Mental Retardation, 106*(5), 470-478.

Donelan, J.M., Kram, R., Kuo, A.D. (2001). Mechanical and metabolic determinants of the preferred step width in human walking. *Proceedings of the Royal Society of London B, 268,* 1985-1992.

Donelan, J.M., Shipman, D.W., Kram, R., Kuo, A.D. (2004). Mechanical and metabolic requirements for active lateral stabilization in human walking. *Journal of Biomechanics, 37,* 827-835.

Farley, C.T., & Ferris, D.P. (1998). Biomechanics of walking and running: Center of mass movements to muscle action. In J.O. Holloszy (Ed.), *Exercise and Sports Science Reviews (Vol. 26, pp. 253-285).* Baltimore: Williams & Wilkins.

Hamill, J., & Knutzen, K.M. (2003). *Biomechanical basis of human movement.* Baltimore: Lippincott Williams & Wilkins.

Kubo, M., & Ulrich, B. (2006a). Coordination of the pelvis-HAT (head, arms and trunk) in anterior-posterior and medio-lateral directions during treadmill gait in preadolescents with/without Down syndrome. *Gait and Posture, 23,* 512-518.

Kubo, M., & Ulrich, B. (2006b). Early stage of walking: Development of control in medio-lateral and anteroposterior directions. *Journal of Motor Control, 38*(3), 229-237.

Kuo, A.D. (1999). Stabilization of lateral motion in passive dynamic walking. *International Journal of Robotics Research, 18,* 917-930.

Latash, M.L. (2000). Motor coordination in Down syndrome: The role of adaptive changes. In D.J. Weeks, R. Chua, & D. Elliott (Eds.), *Perceptual-motor behavior in Down syndrome (pp. 199-223).* Champaign, IL: Human Kinetics.

Latash, M.L., Almeida, G.L., & Corcos, D.M. (1993). Preprogrammed reactions in individuals with Down syndrome: The effects of instruction and predictability of the perturbation. *Archives of Physical Medicine and Rehabilitation, 74,* 391-399.

Latash, M.L., & Anson, J.G. (1996). What are "normal movements" in atypical populations? *Behavioral and Brain Sciences, 19,* 55-106.

Newell, K.M. (1997). Motor skills and mental retardation. In W.E. MacLean, Jr. (Ed.), *Ellis' Handbook of mental deficiency: Psychological theory and research* (pp. 275-308). Mahwah, NJ: Erlbaum.

Newell, K.M., & Jordan, K. (1997). Task constraints and movement organization: A common language. In W.E. Davis & G.D. Broadhead (Eds.), *Ecological Task Analysis and Movement* (pp. 5-23). Champaign, IL: Human Kinetics.

Ounpuu, S. (1994). The biomechanics of walking and running. *Clinics in Sports Medicine, 13(4),* 843-863.

Parker, A.W., & Bronks, R. (1980). Gait of children with Down syndrome. *Archives of Physical Medicine and Rehabilitation, 61,* 345-351.

Roizen, N.J. (2002). Down syndrome. In M.L. Batshaw (Ed.), *Children with disabilities (pp. 307-320).* Baltimore: Paul H. Brooks.

Schieb, D.A. (1986). Kinematic accommodation of novice treadmill runners. *Research Quarterly for Exercise and Sport, 57*(1), 1-7.

Shumway-Cook, A., & Woollacott, M. (1995). *Motor control: Theory and Practical Applications.* Baltimore: Williams & Wilkins.

Sparrow, W.A., & Newell, K.M. (1998). Metabolic energy expenditure and the regulation of movement economy. *Psychonomic Bulletin & Review, 5*(2), 173-196.

Sparrow, W.A., & Day, R.H. (2002). Perception and action in mental retardation. In L.M. Glidden (Ed.), *International review of research in mental retardation* (pp. 241-278). San Diego, CA: Academic Press.

Ulrich, B.D., Haehl, V., Buzzi, U.H., Kubo, M., & Holt, K.G. (2004). Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Human Movement Science, 23,* 133-156.

U.S. Department of Health and Human Services (2000). Healthy people 2010: Understanding and improving health. Washington, DC: U.S. Government Printing Office.

U.S. Department of Health and Human Services (2002). *Closing the gap: A national blueprint to improve the health of persons with mental retardation.* Report of the Surgeon General's Conference on Health Disparities and Mental Retardation. Retrieved January 2, 2007, from http://www.specialolympics.org.

Wall, J.C., & Charteris, J. (1980). The process of habituation to treadmill walking at different velocities. *Ergonomics, 23*(5), 425-435.

Wall, J.C., & Charteris, J. (1981). A kinematic study of long-term habituation to treadmill walking. *Ergonomics, 24*(7), 531-542.

Whipp, B.J., & Wasserman, K. (1969). Efficiency of muscular work. *Journal of Applied Physiology, 26*(5), 644-648.

Winter, D.A. (2005). Biomechanics and motor control of human movement. Hoboken, NJ: John Wiley & Sons.

Table 1. (Table 1 of Manuscript A). Mean ± SD age and anthropometric characteristics of individuals with and without Down syndrome (DS)

	Group	
	DS (n = 15)	Non-DS (n = 15)
Age (years)	27.1 ± 7.6	28.2 ± 5.7
Body mass (kg)	66.1 ± 10.4	70.2 ± 13.4
Height (cm)*	150.1 ± 8.1	171.1 ± 11.7
Leg length (cm)*	72.4 ± 4.7	86.3 ± 7.2
Body Mass Index*	29.2 ± 3.5	23.8 ± 2.9

Note. * = difference between DS and Non-DS statistically significant ($p < 0.05$) in independent t-test.

Table 2. (Table 2 of Manuscript A). Mean ± SD between-stride variability in medio-lateral (y) and vertical (z) COM position, and in anterior-posterior (x) COM velocity across different walking speeds of individuals with and without Down syndrome (DS)

	COMy RMS Standard Deviation† (mm)			COMz RMS Standard Deviation (% body height)			V-COMx RMS Standard Deviation (Froude)		
Froude #	DS	Non-DS	Partial η^2	DS	Non-DS	Partial η^2	DS	Non-DS	Partial η^2
0.1	11.36±4.26	12.26±3.55	.01	.13±.05*	.09±.02	.23	.010±.003*	.007±.001	.29
0.2	11.71±3.21	10.11±2.65	.07	.16±.06*	.10±.02	.31	.012±.004*	.007±.001	.48
0.3	12.50±3.06	10.07±2.56	.17	.17±.07*	.11±.03	.24	.011±.003*	.006±.001	.62
0.4	12.93±3.47	10.71±3.95	.09	.18±.06*	.11±.03	.38	.011±.002*	.006±.001	.59
0.5	13.52±4.32	11.70±4.55	.04	.21±.08*	.10±.02	.47	.011±.003*	.006±.001	.57
0.6	16.65±7.58	11.51±3.31	.17	.28±.09*	.13±.03	.60	.016±.006*	.007±.002	.48
0.7	----------	12.93±3.09	------	----------	.16±.03	------	----------	.009±.001	------

Note. † = significantly larger ($p < 0.05$) in adults with DS as shown by main effect for group in repeated-measures ANOVA; * = difference between DS and Non-DS statistically significant ($p < 0.008$) in one-way ANOVA; COMy = medio-lateral COM position; COMz = vertical COM position; V-COMx = anterior-posterior COM velocity; RMS = Root-mean-square; Froude # = walking speed (for formula see text); Partial η^2 = effect size

Table 3. (Table 3 of Manuscript A). Mean ± SD in step width, step length, and step time at different walking speeds of individuals with and without Down syndrome (DS)

	Step Width (cm)			Step Length (leg lengths)			Step Time (s)		
Froude #	DS	Non-DS	Partial η^2	DS	Non-DS	Partial η^2	DS	Non-DS	Partial η^2
0.1	13.29±4.22	10.03±2.46	.19	.276±.031*	.422±.082	.60	.75±.07*	1.23±.24	.69
0.2	12.39±3.92	9.50±2.32	.18	.448±.041*	.537±.046	.52	.61±.04*	.80±.06	.80
0.3	12.37±4.17	9.83±2.13	.14	.605±.044	.635±.034	.13	.55±.03*	.63±.03	.65
0.4	11.71±4.02	10.18±2.63	.05	.726±.045	.747±.035	.07	.49±.02*	.56±.03	.65
0.5	12.30±4.10	10.76±2.55	.05	.828±.054	.859±.035	.11	.45±.02*	.51±.02	.62
0.6	11.80±3.96	11.08±2.45	.01	.909±.055	.954±.041	.19	.41±.02*	.47±.02	.71
0.7	----------	11.46±2.47	------	----------	1.019±.051	------	----------	.43±.02	------

Note. * = difference between DS and Non-DS statistically significant ($p < 0.008$) in one-way ANOVA; Froude # = walking speed; Partial η^2 = effect size

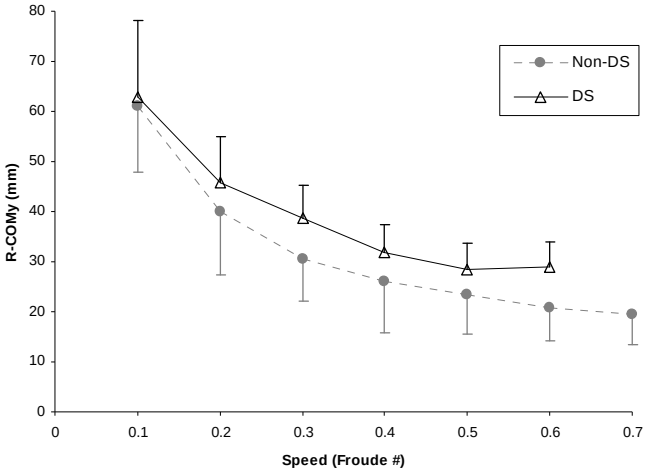
Table 4 (Table 4 of Manuscript A) Mean between-stride variability ± SD step width, step length, and step time at different walking speeds of individuals with and without Down syndrome (DS)

	Step Width Standard Deviation (cm)			Step Length Standard Deviation (leg lengths)			Step Time Standard Deviation (s)		
Froude #	DS	Non-DS	Partial η^2	DS	Non-DS	Partial η^2	DS	Non-DS	Partial η^2
0.1	1.46±.46	1.07±.35	.19	.022±.006	.025±.007	.06	.060±.015	.075±.021	.15
0.2	1.78±.64*	1.15±.31	.30	.027±.007	.021±.007	.17	.037±.008	.031±.010	.09
0.3	1.80±.37*	1.18±.32	.47	.029±.007*	.022±.004	.29	.026±.006	.021±.004	.18
0.4	2.18±.52*	1.24±.35	.55	.027±.006*	.019±.005	.38	.019±.004*	.014±.004	.28
0.5	2.15±.51*	1.28±.35	.51	.030±.006*	.017±.004	.62	.016±.003*	.010±.003	.52
0.6	2.49±.48*	1.51±.45	.54	.031±.005*	.021±.006	.50	.014±.002*	.010±.003	.38
0.7	----------	1.78±.41	------	----------	.028±.013	------	----------	.012±.006	------

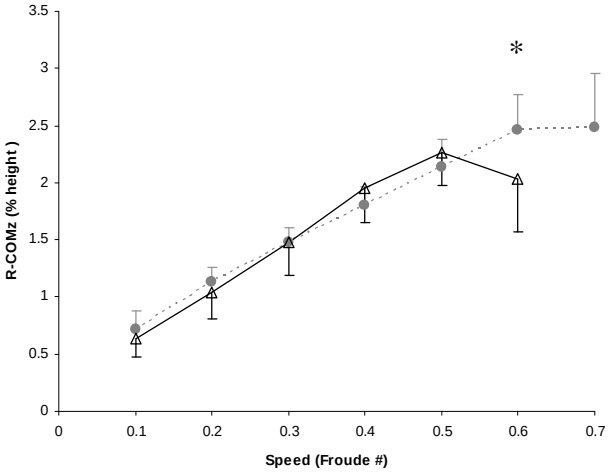
Note. * = difference between DS and Non-DS statistically significant ($p < 0.008$) in one-way ANOVA; Froude # = walking speed; Partial η^2 = effect size

Figure 1. (Figure 1 of Manuscript A). Mean and SD ranges of (a) medio-lateral COM position across stride (R-COMy), (b) vertical COM position across step (R-COMz), and (c) anterior-posterior COM velocity (R-V-COMx) across step as a function of walking speed for adults with and without DS. R-COMy was greater in adults with DS as shown by significant main effect for group ($p<0.05$) in repeated-measures ANOVA. * indicates that R-COMz was shorter in adults only at Froude 0.6 ($p < 0.008$ in one-way ANOVA). R-V-COMx was not different between the groups. Froude # = walking speed.

(a)


R-COMy (mm)
Speed (Froude #)
Non-DS
DS

(b)


R-COMz (% height)
Speed (Froude #)
*

(c)

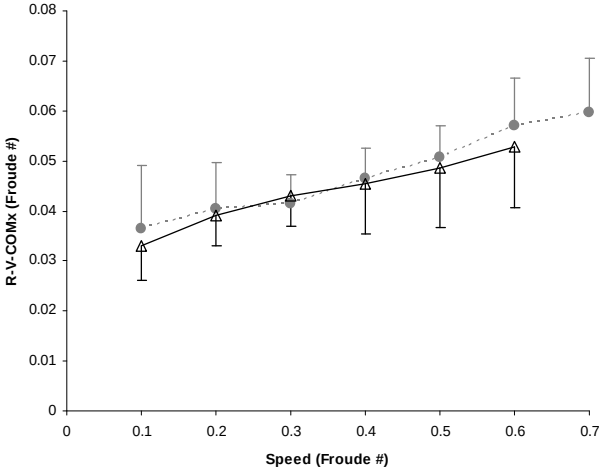
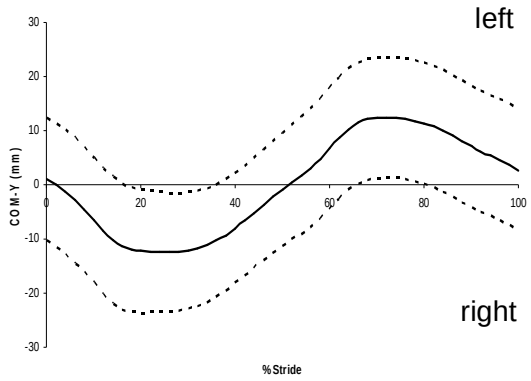

R-V-COMx (Froude #)
Speed (Froude #)

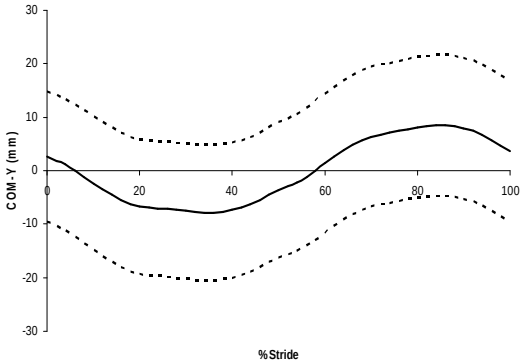
Figure 2. (Figure 2 of Manuscript A). Illustration of average ± between-stride variability (a) medio-lateral COM position (COMy), (b) vertical COM position (COMz), and (c) anterior-posterior COM velocity (V-COMx) across the stride at Froude 0.5 for representative participants with and without DS. Solid and dotted lines show means and standard deviations, respectively. Zero COMy and COMz are averages for each variable. Positive and negative values for V-COMx indicate velocities faster and slower than treadmill speed, respectively. Note that the greater between-stride variability COMy for adults with DS is not seen here.

DS

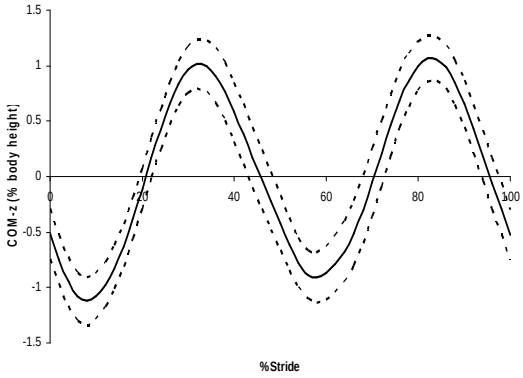
Non-DS

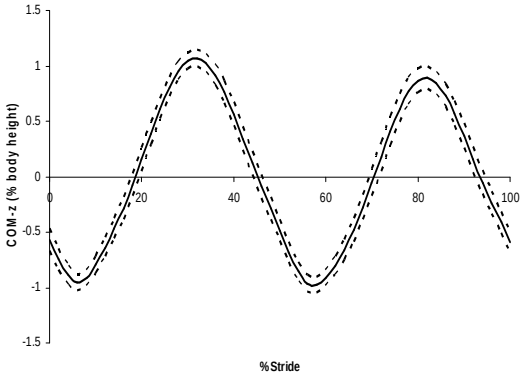
(a)


left
right
COM-Y (mm)
%Stride

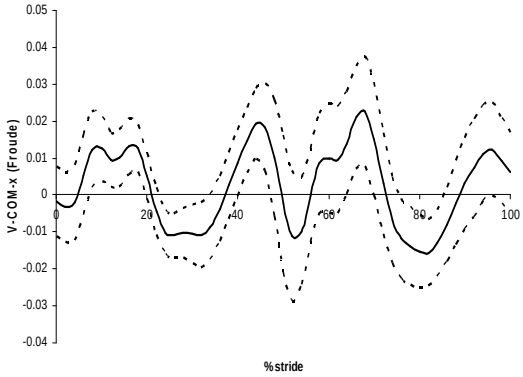

COM-Y (mm)
%Stride

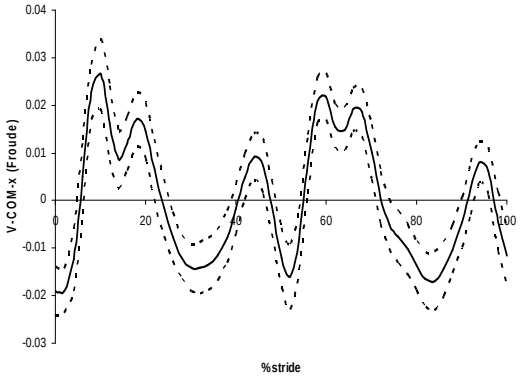
(b)


COM-z (% body height)
%Stride


COM-z (% body height)
%Stride

(c)


V-COM-x (Froude)
%stride


V-COM-x (Froude)
%stride

Chapter 3. Manuscript B

Relative oxygen uptake and oxygen uptake per unit distance across a variety of walking speeds: A comparison between adults with and without Down syndrome

Stamatis Agiovlasitis, Jeffrey A. McCubbin, Jeffrey Widrick, Joonkoo Yun, and Michael J. Pavol

Abstract

This study examined whether the net VO_2 and the net VO_2 per unit distance across a wide range of walking speeds are different between adults with and without Down syndrome (DS). The study also examined the relationship between the energetically optimal walking speed (EOWS) and the preferred walking speed (PWS) in both populations. Respiratory gases were collected from 14 adults with DS and 15 adults without DS as they underwent a series of randomly presented treadmill walking trials each lasting six minutes. Adults with DS walked at dimensionless speeds (Froude numbers) of 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6., with adults without DS also walking at a Froude number of 0.7. EOWS was calculated from the net VO_2 per unit distance to walking speed relationship for each participant. PWS was measured along a 15-meter-long walkway. Adults with DS showed a higher net VO_2 and net VO_2 per unit distance, and a slower EOWS compared to adults without DS. The PWS was the same for both groups and did not appear to minimize the net VO_2 per unit distance in adults with DS. It was concluded that the unique characteristics of adults with DS create an uneconomical walking pattern. Adults with DS do not prefer to walk at speeds that minimize the metabolic demand.

(214 words)

Keywords: *disability, locomotion, energy cost, optimization*

Individuals with Down syndrome (DS) possess unique characteristics that make them prone to decreased walking economy (Cioni, Cocilovo, Rossi, Paci, & Valle, 2001; Parker & Bronks, 1980; Parker, Bronks, & Snyder, 1986; Ulrich, Haehl, Buzzi, Kubo, & Holt, 2004). These are increased joint laxity, muscle hypotonia, pes planus (flat feet), atlanto-axial instability, cerebellum abnormalities, and cognitive limitations (American Academy of Pediatrics, 1995, 2001; Mahan, Diamond, Brown, 1983; Latash, 2000; Newell, 1997; Roizen, 2002). Although walking is a primary means through which persons with DS experience their environments and accumulate daily physical activity necessary to improve health, direct experimental evidence related to their economy during gait is limited. Such empirical information is essential when one considers the central role of walking habits in current health promotion strategies for persons with and without disabilities (Pate et al., 1995; U.S. Department of Health and Human Services, 2000).

Walking economy, which considers the relative rate of oxygen uptake (ml/kg/min) at a given speed (McArdle, Katch, & Katch, 2007) may be affected by the aforementioned unique attributes of individuals with DS. In particular, the joint laxity and muscle hypotonia of children with DS cause gait instability and greater side-to-side motions of the upper-body center of mass (COM) (Buzzi & Ulrich, 2004; Kubo & Ulrich, 2006; Ulrich et al, 2004). These pronounced medio-lateral motions of the COM, which may also be present in the gait of adults with DS, have been hypothesized to contribute to an increased metabolic demand (Saunders, Inman, & Eberhart, 1953). Furthermore, medio-lateral stabilization of the body is an active control process, possibly involving higher centers, that increases the metabolic demand, particularly as step width and step width variability increase (Donelan, Kram, & Kuo, 2001; Donelan, Shipman, Kram, & Kuo, 2004; Kuo, 1999). This metabolic demand may be greater in persons with DS, because they widen their step in order to improve stability and because they may have greater step width variability due to increased variability in their gait kinematics (Parker & Bronks, 1980; Ulrich et al, 2004). Moreover, problems with the cerebellum of individuals with DS can potentially affect the active control processes required for lateral stabilization, thus reducing walking economy (Bauby & Kuo, 2000; Latash, 2000). Another factor that can affect

economy is co-contraction of antagonistic muscle groups, which is common in persons with DS (Latash 2000; Ulrich et al, 2004; Winter, 2005). In addition, individuals with DS have flat feet, decreased motion and smaller moments at the ankle indicating reduced capacity for energy storage and return and less economical walking (Cioni et al., 2001; Mahan et al., 1983; Ulrich et al, 2004;). Intellectual disability and obesity, both common in persons with DS, can independently affect the energetic cost and further intensify the magnitude of decreased economy in this population (Browning, Baker, Herron, & Kram, 2006; Melville, Cooper, McGrother, Thorp, & Collacott, 2005; Ohwada, Nakayama, Suzuki, Yokoyama, & Ishimaru, 2005; Rimmer & Yamaki, 2006).

If walking economy is affected in individuals with DS, then the oxygen uptake required to cover a certain distance (ml/kg/km) may be greater compared to individuals without DS. When the VO_2 per unit distance, also known as the *oxygen cost of transport*, is expressed as a function of walking speed, a U-shaped relationship arises with the nadir occurring at about 1.3 m/s (Bhambhani & Singh, 1985; Margaria, 1976; Ralston, 1958). This energetically optimal walking speed (EOWS) is thought to coincide with the preferred walking speed (PWS) of persons without disabilities (Ralston, 1958). Although a mechanism through which humans sense their EOWS has not been identified empirically, it is thought that it resulted from evolutionary pressure and that it can be refined with practice (Alexander, 1989; Sparrow & Newell, 1998). Similar to the net VO_2, the net VO_2 per unit distance may be greater in persons with DS due to their unique gait characteristics reviewed above. Furthermore, although individuals with DS are generally considered to have a slower preferred walking speed (PWS) than individuals without DS, the possibility that this phenomenon reflects an optimization of the energy cost has not been studied to date (Buzzi & Ulrich, 2004; Cioni et al., 2001; Latash, 2000; Newell, 1997). While some evidence in children with DS suggests that their slower PWS is due to their shorter legs compared to children without DS, the extent to which this applies to adults with DS is presently unknown (Kubo & Ulrich, 2006; Ulrich et al, 2004).

The study of the energetic demand posed on adults with DS during walking may enhance the understanding of the experience of these persons during locomotion

and may allow practitioners to design appropriate walking programs for health and physical activity promotion in this population. Furthermore, movement economy shares important links with motor control and its study can contribute to a theory of motor control in individuals with DS (Sparrow & Newell, 1998).

Within this context, the present study was designed to determine if the rate of oxygen consumption and the oxygen uptake per unit distance across a wide range of walking speeds are different between adults with and without DS. This study also examined whether the EOWS of adults with DS is slower in adults with DS. Furthermore, the degree to which the PWS minimizes the energy cost in both populations was explored. It was hypothesized that adults with DS will show greater net VO_2 and net VO_2 per kilometer across walking speeds and that the PWS will minimize the net VO_2 per kilometer in both populations.

Method

Participants

Participants in this study were 14 adults with DS (7 males and 7 females, age range: 19-44 years) and 15 adults without DS and with no other disability (8 males and 7 females, age range: 18-42 years). The groups of participants with and without DS did not differ in age and body mass. However, participants with DS had greater body mass index and shorter stature and leg length than those without DS (Table 1). Participants with DS were recruited through community-based service programs for individuals with developmental disabilities. These individuals had mild-to-moderate forms of intellectual disability (ID), as confirmed by their parents or direct caregivers. Seven participants with DS lived with their parents, three resided in group homes, and four lived independently. Of the participants with DS, four had congenital heart defects corrected with surgery early in childhood and one had atlanto-axial instability, but no restrictions to physical activity. Given these considerations, participants were in good health as reported by them (non-DS group) or by their parent/direct caregiver (DS group). None of the participants had medical contraindications to exercise. With the exception of a female with DS, the participants were active and exercised regularly. Most participants with DS had part-time jobs requiring physical labor. All participants had some prior experience in the use of a treadmill, except for two

females with DS. Participants and their legal guardians (DS group) provided written informed consent following approval of the study by the Institutional Review Board.

Experimental Design and Procedures

Participants without DS attended two laboratory sessions whereas participants with DS attended three. These sessions were conducted over a period of two to three consecutive weeks for each participant. Oxygen uptake data were collected during the last appointment. The remaining appointment(s) were devoted to PWS determination and to familiarization with the experimental procedures.

In the beginning of the first visit, the PWS was measured. Participants were asked to walk at their comfortable pace towards a target which was at the end of a 15-meter-long walkway. A pair of photo-eyes connected to a timer and placed 5 m apart in the middle of the walkway allowed for the determination of walking speed. Four such trials were performed. Then the body mass, stature, and leg length were measured. Leg length was defined as the height of the right greater trochanter from the floor during standing with shoes on and was measured using an anthropometer (GPM Anthropological Instruments, Zurich, Switzerland). Thereafter, participants were familiarized with the use of breathing masks used for open-circuit spirometry and with the use of the treadmill (Trackmaster TMX22, JAS Manufacturing Inc., Newton, KS). Participants with DS completed six bouts of treadmill walking, each lasting five minutes, at a Froude # of 0.1, 0.2, 0.3, 0.4, 0.5, and 0.6 whereas participants without DS walked for an additional five minutes at a Froude # of 0.7. Earlier work in our lab confirmed that these speeds represent a full range of walking speeds for persons with and without DS, respectively (Agiovlasitis, Yun, Pavol, McCubbin, & Kim, 2007). The Froude number ($F = v / \sqrt{gL}$, where **v** is traveling speed, **g** is the acceleration of gravity, and **L** is leg length) represents speed in dimensionless form and was used to account for known differences in leg length between the groups. This familiarization session and measurement of PWS was conducted once for participants without DS and was repeated on a different day for participants with DS. Collectively, the above procedure allowed for a determination of the repeatability of PWS in individuals with DS between the two visits and it provided 60 and 35 minutes of practice time on the treadmill for participants with and without DS, respectively.

Participants were asked to refrain from food, caffeine, and exercise for two hours prior to the data collection session. The session commenced with a ten-minute sitting period to bring physiologic functions to resting. Thereafter, expired gases were measured during six minutes of quiet standing and during a series of six-minute-long walking trials without hand-rail support, using an open-circuit spirometry system (TrueMax 2400, Parvo Medics, Salt Lake City, UT). The pneumotachometer and the gas analyzers were calibrated prior to each experimental session, using a 3-liter calibration syringe and gases of known concentration, respectively. Gross VO_2 (ml/kg /min) and respiratory exchange ratio (RER) were defined as the respective averages of continuous measurement during the last two minutes of standing and walking trials. The walking trials were performed in a randomized order at the same speeds as during the familiarization session(s) and they were separated by five minutes of sitting. Because one of the participants with DS could not maintain the fastest pace (Froude 0.6) without support, his data at that speed were not included in the analysis.

Data Reduction and Analysis

The PWS for participants in both groups was defined as the average speed of the four over-ground walking trials during the first familiarization session based on the following observations. A t-test showed that the mean PWS of individuals with DS was not different ($t[26] = 0.290$, $p = 0.774$) between the two visits. Moreover, participants with DS were not more variable in PWS during either of the two familiarization sessions, as shown by a non-significant t-test for the difference in the within-person standard deviation of PWS across the four trials between the two sessions ($t[26] = -0.110$, $p = 0.913$).

The relative net VO_2 (ml/kg/min) at each walking speed was calculated by subtracting the resting (standing) VO_2 from the gross VO_2. The oxygen uptake per unit distance (ml/kg/km) was then calculated by dividing the relative net VO_2 by the treadmill speed in km/min. The energetically optimal walking speed (EOWS) for each participant was mathematically determined from individual third order polynomial regressions of the oxygen uptake per kilometer on walking speed (Froude #). The difference between PWS and EOWS was tested with separate t-tests for each group.

Differences in resting VO_2, resting RER, PWS, and EOWS between the DS and non-DS groups were analyzed with simple ANOVA for each of these dependent measures. Differences between the groups in net VO_2, net VO_2 per unit distance, and RER during walking were evaluated using a 2 x 6 (group by speed) ANOVA with repeated measures on the second factor for each variable. In the presence of significant interactions, simple follow-up ANOVA between groups with Bonferroni-adjusted alpha level (0.008) at each speed were performed. To examine if there were within-group differences in the oxygen uptake per unit distance across speeds, pair-wise Bonferroni comparisons following repeated-measures ANOVA were conducted for each group, separately. The Greenhouse-Geisser adjustment was used to correct for violations of the sphericity assumption. The alpha level was set at 0.05. Differences between groups in the above dependent variables were also evaluated by effect sizes, estimated by partial eta squared (η^2). Statistical analysis was conducted using SPSS (version 15.0).

Results

Significant interaction effects were found for net VO_2 (ml/kg/min) ($F[1.7,44.5] = 48.5$; $p < 0.001$), net VO_2 per unit distance ($F[2.0,51.5] = 8.35$; $p = 0.001$), and RER ($F[3.2,84.2] = 16.05$; $p < 0.001$), indicating that the differences in each of these variables between the groups were dependent on walking speed. Follow-up univariate analyses indicated that participants with DS showed higher relative net VO_2 at all speeds with the exception of Froude 0.1 (Figure 1), and higher net VO_2 per unit distance at all walking speeds (Figure 2) than participants without DS. DS explained 19-71% of the variance in net VO_2 and 39-84% of the variance in net VO_2 per unit distance (Table 2). In contrast, RER was greater for DS adults only at Froude 0.6 and showed no difference between the groups at the remaining speeds (Figure 3). Mean differences and effect sizes for the univariate comparisons between the groups in the physiologic measures of interest during walking are included in Table 2.

The above differences were not due to resting relative VO_2 and RER, which were not different between the groups ($F[1, 27] = 1.43$ and 0.46, respectively) (Table 3). Table 3 also shows that EOWS was significantly slower for participants with DS ($F[1, 27] = 12.48$), but PWS did not differ between the groups ($F[1, 27] = 0.06$). Both

participants with and without DS preferred to walk at speeds that were significantly faster than their EOWS ($F[1, 26] = 56.27$, $p < 0.001$, partial $\eta^2 = 0.68$ and $F[1, 28] = 31.99$, $p < 0.001$, partial $\eta^2 = 0.53$, respectively). However, in participants without DS, PWS was within a range that can be considered optimal since there was no significant difference in net VO_2 per kilometer between Froude 0.5 and Froude 0.4. In contrast, visual inspection of Figure 2 indicates that the PWS of participants with DS is higher than their energetically optimal range of speeds.

Discussion

This study examined whether adults with DS have lower walking economy and greater oxygen cost of transport as previously suggested (Cioni et al., 2001; Latash, 2000; Parker et al., 1986; Ulrich et al., 2004). The net VO_2 (ml/kg/min) and the net VO_2 per unit distance (ml/kg/km) were compared between adults with and without DS across a wide range of dimensionless walking speeds (Froude numbers) that were used to normalize for known differences in leg length between the groups. It was hypothesized that these variables would be augmented in adults with DS. Because individuals with DS are generally considered to be slow walkers (Buzzi & Ulrich, 2004; Cioni et al., 2001; Latash, 2000; Newell, 1997), this study also investigated whether their dimensionless PWS is slower than that of individuals without DS. Furthermore, the degree to which adults with DS prefer to walk at speeds that minimize the net VO_2 per kilometer was examined.

The hypothesis that adults with DS are less economical than adults without DS was supported by the present results. Walking posed a significantly greater net VO_2 demand on adults with DS at all speeds except for the slowest one. Arguably, the reduced walking economy of persons with DS is, at least partially, the outcome of their previously documented medio-lateral instability that is caused by increased levels of joint laxity and low muscular tone (Buzzi & Ulrich, 2004; Cioni et al., 2001; Kubo & Ulrich, 2006; Ulrich et al, 2004). Lateral instability requires active control that imparts a metabolic cost as both step width and step width variability increase (Bauby & Kuo, 2000; Donelan et al., 2001, 2004; Kuo, 1999). Persons with DS may thus be less economical because they attempt to improve stability by widening their step and because they may have greater variability in step width due to their more variable

kinematics (Parker & Bronks, 1980; Ulrich et al, 2004). Furthermore, the greater metabolic demand during walking of persons with DS may be intensified by previously suggested problems with the cerebellum that can potentially affect the active control processes required for lateral stabilization (Bauby & Kuo, 2000; Latash, 2000).

Another possibility is that the decreased economy of adults with DS is simply the direct result of pronounced side-to-side motions of the center of mass (COM). It has been theorized that gait kinematic mechanisms produce a smooth sinusoidal pathway of the COM with minimal vertical and medio-lateral displacements during the gait cycle (Saunders et al., 1953). In this way, it was argued, the energy cost required to transport the body forward is minimized. Similar to children with DS, the gait of adults with DS may be characterized by greater side-to-side COM motion and, therefore, increased energetic cost. Moreover, children with DS show higher cadence when walking on the treadmill than children without DS (Ulrich et al., 2004). Increased cadence entails greater frequency of side-to-side motions and a likely exaggeration of the difference in economy between the groups.

Co-contraction of antagonistic muscle groups and increased activation of the upper-body musculature may also contribute to the reduced economy of individuals with DS (McArdle et al., 2007; Winter, 2005). These individuals co-contract their muscles during single joint movements and, possibly, during treadmill walking in order to improve stability, thus increasing the energetic cost (Latash, 2000; Ulrich et al, 2004; Winter, 2005). Furthermore, it is reasonable to hypothesize that, in a population with greater instability, static contractions of the upper-body musculature required for stabilization will be intensified, augmenting the metabolic requirement (McArdle et al., 2007).

An inspection of figure 1 shows that the significant group by speed interaction was more likely the effect of the greater difference in net VO_2 at faster walking speeds. The reason for this differing response of net VO_2 to walking speed between the groups is unclear. One speculation is that it reflects a different stability to walking speed relationship between adults with DS and adults without DS. Another speculation is that it reflects a disproportional increase in cadence as walking speed is increased.

Because cadence generally increases as walking speed is increased (Ounpuu, 1994), the difference in cadence between adults with and without DS may be amplified at faster speeds, thus explaining the group by speed interaction. Such speculations, however, should be empirically tested.

The greater net VO_2 of individuals with DS suggests greater relative effort on their behalf compared to adults without DS. Although not measured in this study, the VO_{peak} of persons with DS is lower than that of persons without disabilities (Fernhall et al., 1996; Pitetti et al., 1992). Therefore, adults with DS walk at higher percentages of their VO_{peak} than their controls across speeds. This implies greater potential for fatigue in persons with DS, particularly if walking is prolonged.

When considering the net VO_2 per unit distance as a function of walking speed, the classic U-shape relationship arose for both groups (Figure 2). Not surprisingly, adults with DS, walked with higher oxygen cost of transport across all speeds. Notably, even the small and insignificant difference of net VO_2 at the slowest speed accumulated into a significant one when the net VO_2 was expressed per unit distance. Similar to the differences in net VO_2, the differences in net VO_2 per unit distance was possibly the effect of increased medio-lateral instability in adults with DS. The significant group by speed interaction indicated that the energetic cost of transport to walking speed relationship was different between the groups. An inspection of Figure 2 and Table 3 shows that this is likely the effect of the widening of the difference at the slowest and fastest speeds. During very slow walking, as at Froude 0.1, adults with DS walk at slower absolute speed (km/min) thus taking a longer time to cover a kilometer than adults without DS. Therefore, the difference in net VO_2 per unit distance becomes magnified. On the other hand, during very fast walking, the difference in net VO_2 per unit distance widens in response to the widening of the difference in net VO_2.

The unique relationship of the oxygen uptake per kilometer to walking speed in adults with DS was more concave, with EOWS occurring at a slower dimensionless speed (Froude #) than in persons without DS (Figure 3). The prediction, however, of optimization theory that this EOWS will coincide with PWS was not met here. Both groups of participants walked at the same PWS relative to their leg length which was

significantly faster than their respective EOWS. However, in participants without DS, PWS was within a range that can be considered optimal. In contrast, the PWS of participants with DS appeared higher than their energetically optimal range of speeds by visual inspection. Consequently, the optimization criteria for the gait of persons with DS appear to be either different or more complex. With greater instability during walking, the primary need of adults with DS may be to ensure stability and, therefore, safety. Notably, research has shown that dynamic stability is improved when children with DS walk on a treadmill at speeds close to their over-ground PWS (Buzzi & Ulrich, 2004). Alternatively, participants with DS may be seeking a walking speed that balances the requirement for both stability and economy. Such balance may be more important when an adult with DS has to cover a long distance and fatigue may set in. It should be noted, however, that these are only speculations since gait stability was not assessed in this study.

A confounding factor that may have contributed to an overestimation of the PWS in this study was that the PWS was measured over a short distance. Although this practice is common in gait research, it may have resulted in a faster than normal PWS due to constraints inherent to the task (Newell & Jordan, 2007). For example, quick completion may be an important constraint for a brief locomotion task and not economy or fatigue. A second limitation was that PWS was measured over-ground whereas testing involved treadmill walking. In fact, it has been argued that the PWS of children with DS is slower on the treadmill than over-ground and the treadmill PWS has been defined as 75% of the over-ground PWS (Ulrich et al, 2004). Interestingly, the 75% of the over-ground PWS for participants with DS in the present investigation falls close to their energetic nadir, providing justification of the energetic optimization hypothesis. However, there is no direct experimental justification for this operational definition of PWS in persons with DS.

It is possible that the increased net VO_2 and net VO_2 per unit distance of adults with DS is partially related to unfamiliarity with treadmill locomotion. To account for this possibility, two familiarization sessions were conducted with participants with DS collectively providing 60 minutes of practice time on the treadmill. Although this amount of practice is significantly more that the 30 minutes recommended for persons

without disabilities (Charteris & Taves, 1978; Schieb, 1986; Wall & Charteris, 1980, 1981), the exact amount of familiarization required for persons with DS is presently unknown. Furthermore, the degree to which the differences in the energetic demand during treadmill walking apply to over-ground locomotion should be tested empirically. Other confounding factors for the observed differences in net VO_2 and net VO_2 per unit distance include intellectual disability and obesity, both attributes of individuals with DS, that have been shown to affect the metabolic cost (Browning et al., 2006; Melville et al., 2005; Ohwada et al., 2005; Rimmer & Yamaki, 2006). However, these confounding factors have smaller effects than the ones observed in this study, suggesting that the specific gait characteristics of adults with DS cause an additional energetic cost. The increased net VO_2 and net VO_2 per unit distance of adults with DS in this study does not appear to be caused by differences in fuel utilization as suggested by the similar RER between the groups at most walking speeds. Moreover, the significantly higher RER of 0.99 at Froude 0.6 in individuals with DS indicates a primary dependence on carbohydrate metabolism which requires less oxygen uptake than fat metabolism to liberate a given amount of energy (McArdle et al., 2007). Such dependence on carbohydrate metabolism would have had the effect of reducing the net VO_2 and act counter to the observations made herein.

In conclusion, the net VO_2 and the net VO_2 per unit distance across a wide range of walking speeds are both greater in adults with DS compared to adults without DS. Among the inherent characteristics of individuals with DS that can contribute to these observations are increased joint laxity and muscle hypotonia which have been hypothesized to create an unstable and thus uneconomical gait pattern. The previous suggestion that individuals with DS have a preference for slow walking speeds is explained by their shorter legs. Adults with DS prefer to walk at a speed that is faster than their energetically optimal one. The exact reasons for this are unclear, but they could be related to improved stability at PWS. These results improve our understanding of the physiological response to walking of adults with DS and should be considered when designing walking programs to promote their health.

References

Agiovlasitis, S., Yun, J., Pavol, M.J., McCubbin, J.A., & Kim, S. (2007). *Gait transitions of persons with and without intellectual disability*. Manuscript submitted for publication.

Alexander, R. M. (1989). Optimization and gaits in the locomotion of vertebrates. *Physiological Reviews, 69*(4), 1199-1227.

American Academy of Pediatrics, Committee on Sports Medicine and Physical Fitness, (1995). Atlantoaxial instability in Down syndrome: A subject review. *Pediatrics, 96*(1), 151-154.

American Academy of Pediatrics, Committee on Genetics, (2001). Health supervision of children with Down syndrome. *Pediatrics, 107*(2), 442-449.

Bauby, C.E., & Kuo, A.D. (2000). Active control of lateral balance in human walking. *Journal of Biomechanics, 33,* 1433-1440.

Bhambhani, Y., & Singh, M. (1985). Metabolic and cinematographic analysis of walking and running in men and women. *Medicine and Science in Sports and Exercise, 17*(1), 131-137.

Browning, R.C., Baker, E.A., Herron, J.A. & Kram, R. (2005). Effects of obesity and sex on the energetic cost and preferred speed of walking. *Journal of Applied Physiology, 100*, 390-398.

Buzzi, U.H., & Ulrich, B.D. (2004). Dynamic stability of gait cycles as a function of speed and system constraints. *Motor Control, 8,* 241-254.

Charteris, J., & Taves, C. (1978). The process of habituation to treadmill walking: a kinematic analysis. *Perceptual and Motor Skills, 47,* 659-666.

Cioni, M., Cocilovo, A., Rossi, F., Paci, D., & Valle, M.S. (2001). Analysis of ankle kinetics during walking in individuals with Down syndrome. *American Journal of Mental Retardation, 106*(5), 470-478.

Donelan, J.M., Kram, R., Kuo, A.D. (2001). Mechanical and metabolic determinants of the preferred step width in human walking. *Proceedings of the Royal Society of London B, 268,* 1985-1992.

Donelan, J.M., Shipman, D.W., Kram, R., Kuo, A.D. (2004). Mechanical and metabolic requirements for active lateral stabilization in human walking. *Journal of Biomechanics, 37,* 827-835.

Fernhall, B., Pitetti, K.H., Rimmer, J.H., McCubbin, J.A., Rintala, P., Millar, A.L., et al. (1996). Cariorespiratory capacity of individuals with mental retardation including Down syndrome. *Medicine and Science in Sports and Exercise, 28*(3), 366-371.

Kubo, M., & Ulrich, B. (2006). Coordination of the pelvis-HAT (head, arms and trunk) in anterior-posterior and medio-lateral directions during treadmill gait in preadolescents with/without Down syndrome. *Gait and Posture, 23,* 512-518.

Kuo, A.D. (1999). Stabilization of lateral motion in passive dynamic walking. *International Journal of Robotics Research, 18,* 917-930.

Latash, M.L. (2000). Motor coordination in Down syndrome: The role of adaptive changes. In D.J. Weeks, R. Chua, & D. Elliott (Eds.), *Perceptual-motor behavior in Down syndrome (pp. 199-223).* Champaign, IL: Human Kinetics.

Mahan, K.T., Diamond, E., & Brown, D. (1983). Podiatric profile of the Down's syndrome individual. *Journal of the American Podiatry Association, 73*(4), 173-179.

Margaria, R. (1976). *Biomechanics and energetics of muscular exercise.* Oxford: Clarendon Press.

McArdle, W.D., Katch F.I., & Katch, V.L. (2007). *Exercise physiology: Energy, nutrition, and human performance*. Baltimore: Lippincott Williams & Wilkins.

Melville, C.A., Cooper, S.-A., McGrother, C.W., Thorp, C.F., & Collacott, R. (2005). Obesity in adults with Down syndrome: A case control study. *Journal of Intellectual Disability Research, 49*(2), 125-133.

Newell, K.M. (1997). Motor skills and mental retardation. In W.E. MacLean, Jr. (Ed.), *Ellis' Handbook of mental deficiency: Psychological theory and research* (pp. 275-308). Mahwah, NJ: Erlbaum.

Newell, K.M., & Jordan, K. (2007). Task constraints and movement organization: A common language. In W.E. Davis & G.D. Broadhead (Eds.), *Ecological Task Analysis and Movement* (pp. 5-23). Champaign, IL: Human Kinetics.

Ohwada, H., Nakayama, T., Suzuki, Y., Yokoyama, T. & Ishimaru, M. (2005). Energy expenditure in males with mental retardation. *Journal of Nutritional Science and Vitaminology, 51,* 68-74.

Ounpuu, S. (1994). The biomechanics of walking and running. *Clinics in Sports Medicine, 13(4),* 843-863.

Parker, A.W., & Bronks, R. (1980). Gait of children with Down syndrome. *Archives of Physical Medicine and Rehabilitation, 61,* 345-351.

Pate, R.R., Pratt, M., Blair, S.N., Haskell, W.L., Macera, C.A., Bouchard, C., et al. (1995). Physical activity and public health. A recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. *JAMA, 273*(5), 402-407.

Pitetti, K.H., Climstein, M., Campbell, K.D., Barrett, P.J., & Jackson, J.A. (1992). The cardiovascular capacities of adults with Down syndrome: A comparative study. *Medicine and Science in Sports and Exercise, 24*(1), 13-19.

Ralston, H.J. (1958). Energy-speed relation and optimal speed during level walking. *Int. Z. angew. Physiol.,* 17, 277-288.

Rimmer, J.H., & Yamaki, K. (2006). Obesity and intellectual disability. *Mental Retardation and Developmental Disabilities Research Reviews, 12,* 22-27.

Roizen, N.J. (2002). Down syndrome. In M.L. Batshaw (Ed.), *Children with disabilities (pp. 307-320).* Baltimore: Paul H. Brooks.

Schieb, D.A. (1986). Kinematic accommodation of novice treadmill runners. *Research Quarterly for Exercise and Sport, 57*(1), 1-7.

Sparrow, W.A., & Newell, K.M. (1998). Metabolic energy expenditure and the regulation of movement economy. *Psychonomic Bulletin & Review, 5*(2), 173-196.

Sparrow, W.A., & Day, R.H. (2002). Perception and action in mental retardation. In L.M. Glidden (Ed.), *International review of research in mental retardation* (pp. 241-278). San Diego, CA: Academic Press.

Ulrich, B.D., Haehl, V., Buzzi, U.H., Kubo, M., & Holt, K.G. (2004). Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Human Movement Science, 23,* 133-156.

U.S. Department of Health and Human Services (2000). Healthy people 2010: Understanding and improving health. Washington, DC: U.S. Government Printing Office.

Wall, J.C., & Charteris, J. (1980). The process of habituation to treadmill walking at different velocities. *Ergonomics, 23*(5), 425-435.

Wall, J.C., & Charteris, J. (1981). A kinematic study of long-term habituation to treadmill walking. *Ergonomics, 24*(7), 531-542.

Winter, D.A. (2005). Biomechanics and motor control of human movement. Hoboken, NJ: John Wiley & Sons.

Table 5. (Table 1 of Manuscript B). Mean ± SD of age and anthropometric characteristics of individuals with and Down syndrome (DS)

	Group		
	DS (n = 14)	Non-DS (n = 15)	p-value
Age (years)	27.7 ± 7.5	28.2 ± 5.7	0.846
Body mass (kg)	65.6 ± 10.6	70.2 ± 13.4	0.319
Stature (cm)*	149.4 ± 7.9	171.1 ± 11.7	0.000
Leg length (cm)*	72.4 ± 4.8	86.3 ± 7.2	0.000
Body Mass Index*	29.3 ± 3.6	23.8 ± 2.9	0.000

Note. * = difference between DS and Non-DS statistically significant ($p < 0.05$) in independent t-test.

Table 6. (Table 2 of Manuscript B). Mean differences ± SE and effect sizes across walking speeds for the comparisons in physiologic variables between adults with and without Down syndrome (DS)

	Net VO_2 (ml/kg/min)		VO_2 / km (ml/kg/km)		RER	
Froude #	Difference	Partial η^2	Difference	Partial η^2	Difference	Partial η^2
0.1	0.49 ± 0.20	0.19	44.46 ± 10.65*	0.39	0.00 ± 0.02	0.00
0.2	0.67 ± 0.20*	0.29	30.47 ± 5.35*	0.55	0.01 ± 0.02	0.01
0.3	0.73 ± 0.25*	0.24	23.90 ± 4.52*	0.51	0.01 ± 0.02	0.02
0.4	1.45 ± 0.28*	0.50	29.97 ± 3.65*	0.71	0.03 ± 0.02	0.12
0.5	2.49 ± 0.44*	0.54	40.00 ± 4.61*	0.74	0.04 ± 0.02	0.23
0.6	4.52 ± 0.57*	0.71	57.34 ± 4.98*	0.84	0.13 ± 0.02*	0.59

Note. Difference = DS – Non-DS; * = difference between DS and Non-DS statistically significant ($p < 0.008$) in one-way ANOVA; Partial η^2 = effect size; Net VO_2 = net relative oxygen uptake; RER = respiratory exchange ratio; VO_2 / km = oxygen uptake per unit distance; Froude # = walking speed

Table 7. (Table 3 of Manuscript B). Mean ± SD of preferred and energetically optimal walking speeds, and resting physiologic characteristics of individuals with and without Down syndrome (DS)

	Group			
	DS	Non-DS	p-value	Partial η^2
PWS (Froude #)	0.48 ± 0.07†	0.48 ± 0.07 †	0.805	0.00
EOWS (Froude #)*	0.34 ± 0.02	0.38 ± 0.03	0.001	0.32
$VO_{2\ Rest}$ (ml/kg/min)	3.45 ± 0.49	3.70 ± 0.63	0.243	0.05
RER_{Rest}	0.86 ± 0.06	0.88 ± 0.07	0.504	0.02

Note. * = difference between DS and Non-DS statistically significant ($p < 0.05$) in one-way ANOVA; † = difference between PWS and EOWS statistically significant ($p < 0.05$) in independent t-test; PWS = preferred walking speed; EOWS = energetically optimal walking speed; $VO_{2\ Rest}$ = standing relative oxygen uptake; RER_{Rest} = standing respiratory exchange ratio; Partial η^2 = effect size.

Figure 3. (Figure 1 of Manuscript B). Mean ± SD of net oxygen uptake as a function of walking speed in adults with and without Down syndrome (DS). * indicates significant difference between the groups ($p < 0.008$) in one-way ANOVA. Curves are second order polynomials fitted to means for adults with DS [$VO_2 = 52.577\ (F)^2 - 11.278\ (F) + 3.815$, $R^2 = 0.99$] and adults without DS [Net $VO_2 = 46.692\ (F)^2 - 13.262\ (F) + 3.745$, $R^2 = 0.99$]; Froude # = walking speed (for formula see text).

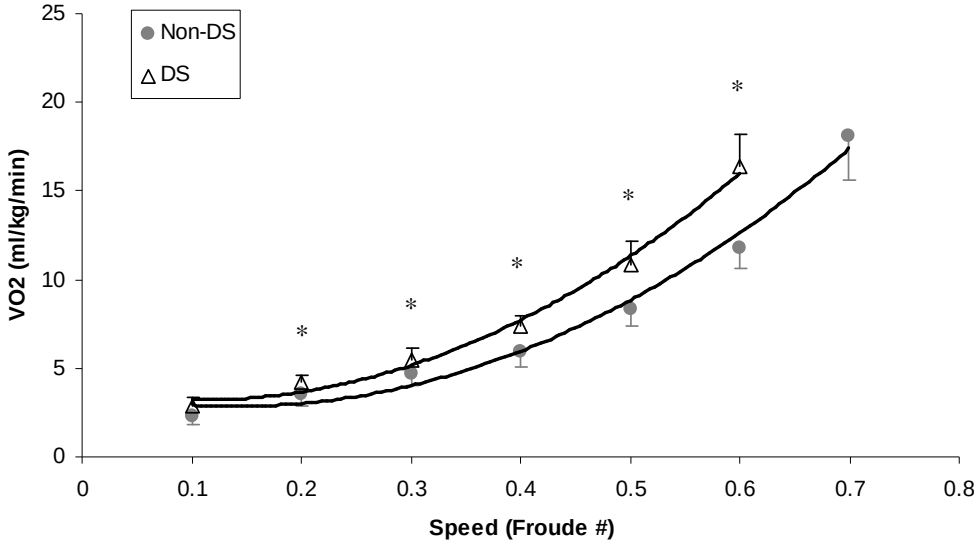

Non-DS
DS
VO2 (ml/kg/min)
Speed (Froude #)
0
5
10
15
20
25
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
*
*
*
*
*

Figure 4. (Figure 2 of Manuscript B). Mean ± SD of oxygen uptake per unit distance as a function of walking speed in adults with and without Down syndrome (DS). * indicates significant difference between the groups ($p < 0.008$) in one-way ANOVA. † indicates significant difference from speed immediately before in Bonferroni contrasts for this group. Black solid and grey dotted vertical lines indicate the energetically optimal walking speed (EOWS) in adults with and without DS, respectively. The preferred walking speed (PWS) of both groups is also shown. Curves are third order polynomials fitted to means for adults with DS [Net VO_2 (ml/kg/km) = - 628.56 $(F)^3$ + 1656.1 $(F)^2$ – 903.85 (F) + 252.24, $R^2 = 1.0$] and adults without DS [VO_2 (ml/kg/km) = - 61.24 $(F)^3$ + 682.7 $(F)^2$ – 486.28 (F) + 174.47, $R^2 = 1.0$]; Froude # = walking speed.

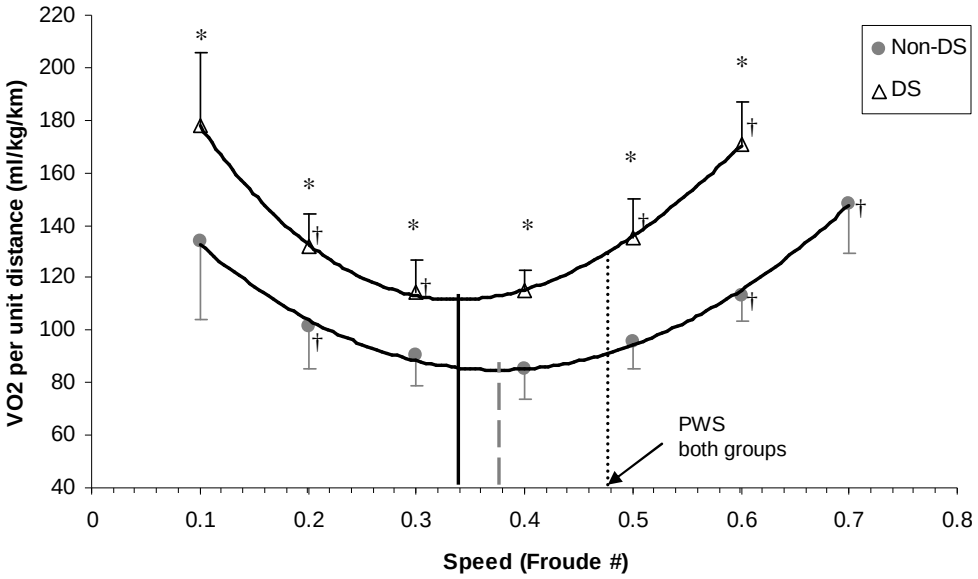
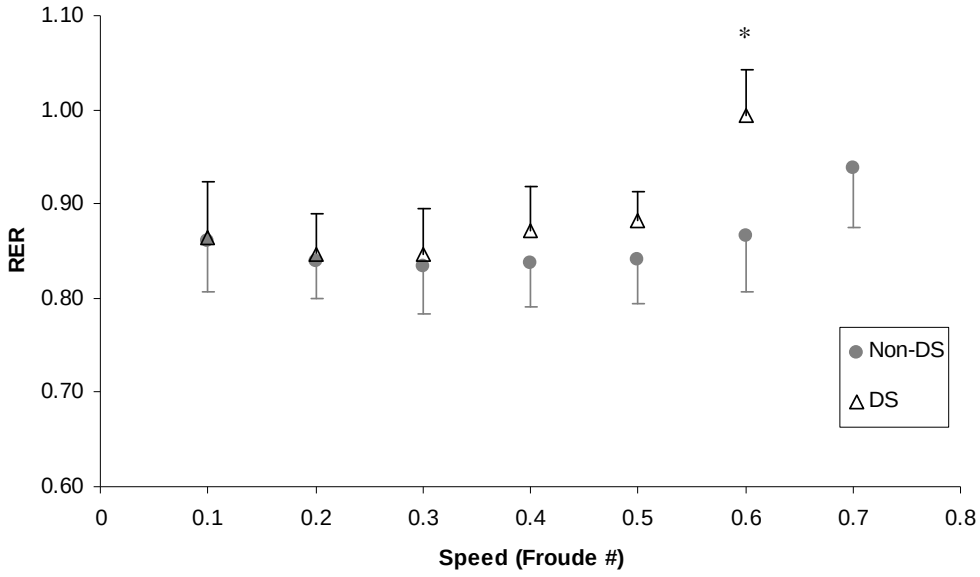

220
200
180
160
140
120
100
80
60
40
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
VO2 per unit distance (ml/kg/km)
Speed (Froude #)
Non-DS
DS
PWS
both groups

Figure 5. (Figure 3 of Manuscript B). Mean ± SD of respiratory exchange ratio (RER) as a function of walking speed in adults with and without Down syndrome (DS). * indicates significant difference between the groups ($p < 0.008$) in one-way ANOVA. Froude # = walking speed.


1.10
1.00
0.90
0.80
0.70
0.60
RER
*
Non-DS
DS
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Speed (Froude #)

Chapter 4. Conclusions and Future Directions

The walking pattern of individuals with the genetic abnormality identified as Down syndrome (DS) has been previously hypothesized to be inefficient (American Academy of Pediatrics, 1995; Cioni, Cocilovo, Rossi, Paci, & Valle, 2001; Parker & Bronks, 1980; Parker, Bronks, & Snyder, 1986; Ulrich, Haehl, Buzzi, Kubo, & Holt, 2004). Gait inefficiency is generally thought to result from increased instability, particularly in the medio-lateral direction, due to the characteristic joint laxity, muscle hypotonia, and cerebellum abnormalities of individuals with DS (American Academy of Pediatrics, 1995, 2001; Buzzi & Ulrich, 2004; Kubo & Ulrich, 2006; Latash, 2000; Newell, 1997; Roizen, 2002). Despite a multitude of medical complications associated with DS, the life expectancy of individuals with DS has increased dramatically due to advances in medical science (American Academy of Pediatrics, 2001; Roizen, 2002). In California, for example, the median age at death of persons with DS increased from 23 years in 1987 to 49 years in 1997 (Yang, Rasmussen, & Friedman, 2002). Therefore, a larger number of adults with DS live among us compared to previous decades. These adults who are at increased risk of preventable mortality and morbidity experience disparities in health care, including fewer opportunities for physical activity and exercise (Melville, Cooper, McGrother, Thorp, & Collacott, 2005; Rimmer, & Yamaki, 2006; Stanish, Temple, & Frey, 2006; Sutherland, Couch, & Iacono, 2002; U.S. Department of Health and Human Services, 2002). Because walking habits are at the center of current health promotion strategies for persons with and without disabilities, better informed and more effective programs for promoting health in adults with DS are likely to result from an improved understanding of gait in these individuals (Pate et al., 1995; U.S. Department of Health and Human Services, 2000). The study of walking efficiency, in particular, can enhance our understanding of the effort required from adults with DS during locomotion.

To gain insight into the efficiency of gait in adults with DS, this study examined the three-dimensional motion of the center of mass (COM), the spatio-temporal characteristics, and energetic cost during treadmill walking at a variety of speeds. It was hypothesized that adults with DS would show greater and more variable medio-lateral COM motions due to their previously hypothesized instability accompanied by greater step-width variability. A more variable pattern in anterior-

posterior COM velocity and vertical COM displacement was also anticipated by adults with DS. It was further hypothesized that adults with DS would show greater net VO_2 and net VO_2 per unit distance across a range of walking speeds. Moreover, because individuals with DS are generally considered to be slow walkers (Buzzi & Ulrich, 2004; Latash, 2000), it was hypothesized that their preferred walking speed (PWS) would coincide with their energetically optimal walking speed (EOWS) which would be slower than that of individuals without DS.

Fifteen adults with DS and 15 adults without DS walked on a treadmill at six and seven randomly presented dimensionless speeds (Froude numbers), respectively. Their PWS, three-dimensional COM motion, and oxygen uptake were assessed during separate appointments. It was found that the range of medio-lateral COM position was greater in participants with DS, but the ranges of vertical COM position and anterior-posterior COM velocity did not differ between the groups (with the exception of the range of vertical COM position at Froude 0.6). Participants with DS walked with faster steps across all speeds. Their step length was shorter only during slow walking and their step width did not differ from adults without DS. Participants with DS were more variable between strides in medio-lateral and vertical COM position, in anterior-posterior COM velocity, and in spatio-temporal parameters than their controls. In addition, adults with DS showed a higher net VO_2 and net VO_2 per unit distance, and a slower EOWS compared to adults without DS. The PWS was the same for both groups and did not appear to minimize the net VO_2 per unit distance in adults with DS.

The larger range of medio-lateral COM range of adults with DS is likely a manifestation of the gait instability associated with DS. Medio-lateral COM motion has been shown to distinguish elderly individuals with reduced balance and has also been hypothesized to show instability in children with DS (Chou, Kaufman, Hahn, & Brey, 2003, Kubo & Ulrich, 2006). One may add that the increased instability of adults with DS is also manifested in the more variable and thus unpredictable medio-lateral, vertical, and anterior-posterior motion of their COM between strides. Enhanced side-to-side motions may increase the energetic demand to redirect COM within a safe margin. Furthermore, a more variable COM motion in all planes may contribute to a less consistent and thus less efficient forward progression. Therefore, it

appears that forward progression has an augmented energetic demand in adults with DS.

To accommodate their unstable and unpredictable COM motion, adults with DS appear to vary their foot placement from step to step. This increased spatial variability is suggestive of an increased active control required for gait stabilization (Bauby & Kuo, 2000; Shumway-Cook & Woollacott, 1995). Because this active strategy has been shown to have an energetic cost (Donelan, Shipman, Kram, & Kuo, 2004), it follows that the efficiency of gait in adults with DS may be negatively impacted. However, this increased variability should not be directly corrected by therapists since it appears to be a functional adaptation to instability (Latash & Anson, 1996).

Since forward progression in adults with DS appear to be characterized by an inefficient movement pattern, it is not surprising that the net VO_2 and the net VO_2 per unit distance across a wide range of dimensionless walking speeds were both greater in adults with DS than in adults without DS. These variables provide practical measures of the ease of walking and are used when designing exercise programs for individuals with and without disabilities (McArdle, Katch, & Katch, 2007). From a practical standpoint, health promotion specialists should be aware that, when an adult with DS and an adult without DS walk at the same speed relative to their differing leg lengths (Froude number), the adult with DS will walk slower in absolute terms and she/he will continuously fall behind. In spite of this, however, the adult with DS expends considerably more energy than the adult without DS. When these two individuals are asked to cover a kilometer side-by-side at the same absolute speed, the difference in the energetic cost between them is further magnified. Such practice may be particularly fatiguing for the adult with DS and may negatively impact exercise adherence. Conclusively, the effort put forth during locomotion by adults with DS is significantly higher than that of adults without DS.

Although adults with DS demonstrated a unique relationship of the net VO_2 per unit distance to walking speed, with an EOWS that was slower than that of their controls, their PWS did not appear to minimize the energetic cost of transport. Therefore, it appears that the optimization criteria for the gait of persons with DS

appear to be either more complex or not directly related to the energy expenditure. With greater instability during walking, the primary need of adults with DS may be to ensure stability and, therefore, safety. Alternatively, a balance between stability and economy may be sought by adults with DS. However, these are only speculations since gait stability was not assessed in this study. Since PWS was the same between the groups, the suggestion that individuals with DS walk slower than individuals without DS (Buzzi & Ulrich, 2004; Latash, 2000) does not hold and is largely explained by the fact that adults with DS have shorter legs.

In summary, the gait pattern of adults with DS is characterized by an affected COM motion, particularly in the medio-lateral direction, that requires an increased energetic cost. The increased movement variability extends to spatio-temporal variables reflecting increased active control of unstable motions that may intensify the metabolic requirement. Therefore, individuals with DS walk with greater net VO_2 and net VO_2 per unit distance compared to adults without DS. Although adults with DS have a slower EOWS, they prefer to walk at the same speeds as adults without DS.

In interpreting these findings the following limitations should be considered:

- The lack of random sampling may negatively affect the external validity of the results.
- This study used treadmill locomotion that can potentially affect its ecological validity.
- Participants without DS had greater prior experience with treadmill walking than the participants with DS.
- The amount of treadmill walking practice provided to participants with DS may not have been enough in reducing variability in COM motion due to unfamiliarity with treadmill locomotion.
- The degree to which the PWS as measured in this study reflects the true generally preferred walking speed for adults with and without DS is unknown.
- The over-ground preferred walking speed may be different from the preferred walking speed on the treadmill in adults with DS.

- The measurement of V-COMx as presented here assumes a constant treadmill speed. However, treadmill speed continuously varies to some extent.
- The validity of the Plug-In-Gait model used to estimate COM position in adults with DS may be questionable if these individuals possess a unique anthropomorphy.
- The observed differences in net VO_2 and net VO_2 per unit distance may be confounded by intellectual disability and obesity, both attributes of individuals with DS that have been shown to affect the metabolic cost.

To counteract these limitations, the following delimitations were applied:

- In the context of adapted physical activity research, the sample size may be considered adequate.
- The experimental group included most individuals with DS in this geographic area that met the inclusion criteria, thus increasing representative-ness.
- An additional familiarization session was conducted for participants with DS.
- The PWS was measured on two occasions for participants with DS and was found to be consistent between these measurements.
- In participants without DS, the PWS was also measured on the treadmill and no difference from the over-ground PWS was observed.
- A large number of strides were included in kinematic data analysis for each participant.

The paucity of research in the gait pattern of adults with DS make the descriptive findings presented here important first steps in understanding how these individuals experience locomotion. Future research, however, should attempt to offer explanations for the observations of this study. The relationship between the physiological characteristics of adults with DS (e.g., joint laxity and muscle hypotonia) and their inefficient gait should be empirically identified. Furthermore, the degree to which appropriate interventions can improve walking efficiency and economy and facilitate favorable health outcomes in adults with DS should be explored. More important, the ecological validity of this type of research will be

improved if adults with DS are studied in real world settings. In this context, suggestions for future research include the following research questions:

- Do the results presented here apply to over-ground locomotion?
- How are joint laxity and muscle hypotonia related to gait instability in adults with DS?
- What mechanical and motor factors better predict the increased metabolic demand during walking in adults with DS?
- What is the dynamic stability of adults with DS across walking speeds?
- What is the mechanical efficiency of adults with DS during walking at an incline? Mechanical efficiency can be calculated when walking at an incline, but not during level walking.
- What is the caloric expenditure during walking in adults with DS?
- Does the PWS optimize other factors such as stability in adults with DS?
- Is the PWS the same when measured under different conditions in adults with DS?
- Does lateral stabilization during treadmill walking decrease the energetic cost in adults with DS?
- Does lateral stabilization during treadmill walking training improve health and fitness outcomes, as well as program compliance and adherence in adults with DS?
- Does lateral stabilization during early intervention treadmill walking training facilitate the onset of walking in children with DS?
- How does the increased metabolic cost of adults with DS relate to their levels of physical activity?
- Is the increased energetic demand of walking a barrier that inhibits adults with DS from participating in physical activities?
- What is the relationship between the product of intensity, frequency, and duration of walking to morbidity and mortality in adults with DS?
- How can architectural improvements facilitate walking behaviors in individuals with DS as a means of transporting themselves in rural and urban environments?

References

American Academy of Pediatrics, Committee on Sports Medicine and Physical Fitness, (1995). Atlantoaxial instability in Down syndrome: A subject review. *Pediatrics, 96*(1), 151-154.

American Academy of Pediatrics, Committee on Genetics, (2001). Health supervision of children with Down syndrome. *Pediatrics, 107*(2), 442-449.

Bauby, C.E., & Kuo, A.D. (2000). Active control of lateral balance in human walking. *Journal of Biomechanics, 33,* 1433-1440.

Browning, R.C., Baker, E.A., Herron, J.A. & Kram, R. (2005). Effects of obesity and sex on the energetic cost and preferred speed of walking. *Journal of Applied Physiology, 100,* 390-398.

Buzzi, U.H., & Ulrich, B.D. (2004). Dynamic stability of gait cycles as a function of speed and system constraints. *Motor Control, 8,* 241-254.

Cavanagh, P.R., & Kram, R. (1985). The efficiency of human movement – a statement of the problem. *Medicine and Science in Sports and Exercise, 17*(3), 304-308.

Cioni, M., Cocilovo, A., Rossi, F., Paci, D., & Valle, M.S. (2001). Analysis of ankle kinetics during walking in individuals with Down syndrome. *American Journal of Mental Retardation, 106*(5), 470-478.

Donelan, J.M., Shipman, D.W., Kram, R., & Kuo, A.D. (2004). Mechanical and metabolic requirements for active lateral stabilization in human walking. *Journal of Biomechanics, 37,* 827-835.

Kubo, M., & Ulrich, B. (2006). Coordination of the pelvis-HAT (head, arms and trunk) in anterior-posterior and medio-lateral directions during treadmill gait in preadolescents with/without Down syndrome. *Gait and Posture, 23,* 512-518.

Kuo, A.D. (1999). Stabilization of lateral motion in passive dynamic walking. *International Journal of Robotics Research, 18,* 917-930.

Latash, M.L. (2000). Motor coordination in Down syndrome: The role of adaptive changes. In D.J. Weeks, R. Chua, & D. Elliott (Eds.), *Perceptual-motor behavior in Down syndrome (pp. 199-223).* Champaign, IL: Human Kinetics.

McArdle, W.D., Katch, F.I., & Katch, V.L. (2007). *Exercise physiology: Energy, nutrition, and human performance*. Baltimore: Lippincott Williams & Wilkins.

Melville, C.A., Cooper, S.-A., McGrother, C.W., Thorp, C.F., & Collacott, R. (2005). Obesity in adults with Down syndrome: A case control study. *Journal of Intellectual Disability Research, 49*(2), 125-133.

Parker, A.W., & Bronks, R. (1980). Gait of children with Down syndrome. *Archives of Physical Medicine and Rehabilitation, 61,* 345-351.

Pate, R.R., Pratt, M., Blair, S.N., Haskell, W.L., Macera, C.A., Bouchard, C., et al. (1995). Physical activity and public health. A recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. *JAMA, 273*(5), 402-407.

Rimmer, J.H., & Yamaki, K. (2006). Obesity and intellectual disability. *Mental Retardation and Developmental Disabilities Research Reviews, 12,* 22-27.

Roizen, N.J. (2002). Down syndrome. In M.L. Batshaw (Ed.), *Children with disabilities (pp. 307-320).* Baltimore: Paul H. Brooks.

Stanish, H.I., Temple, V.A., & Frey, G.C. (2006). Health-promoting physical activity of adults with mental retardation. *Mental Retardation and Developmental Disabilities Research Reviews, 12,* 13-21.

Sutherland, G., Couch, M.A., & Iacono, T. (2002). Health issues for adults with developmental disability. *Research in Developmental Disabilities, 23,* 422-445.

Ulrich, B.D., Haehl, V., Buzzi, U.H., Kubo, M., & Holt, K.G. (2004). Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Human Movement Science, 23,* 133-156.

U.S. Department of Health and Human Services (2000). Healthy people 2010: Understanding and improving health. Washington, DC: U.S. Government Printing Office.

U.S. Department of Health and Human Services (2002). *Closing the gap: A national blueprint to improve the health of persons with mental retardation.* Report of the Surgeon General's Conference on Health Disparities and Mental Retardation. Retrieved January 2, 2007, from http://www.specialolympics.org.

Yang, Q., Rasmussen, S.A., & Friedman, J.M. (2002). Mortality associated with Down's syndrome in the USA from 1983 to 1997: A population based study. *Lancet, 359,* 1019-1025.

BIBLIOGRAPHY

Bibliography

Agiovlasitis, S., Yun, J., Pavol, M.J., McCubbin, J.A., & Kim, S. (2007). *Gait transitions of persons with and without intellectual disability*. Manuscript submitted for publication.

Alexander, R. M. (1984). Walking and running. *American Scientist, 72,* 1199-1227.

Alexander, R. M. (1989). Optimization and gaits in the locomotion of vertebrates. *Physiological Reviews, 69*(4), 1199-1227.

American Academy of Pediatrics, Committee on Sports Medicine and Physical Fitness, (1995). Atlantoaxial instability in Down syndrome: A subject review. *Pediatrics, 96*(1), 151-154.

American Academy of Pediatrics, Committee on Genetics, (2001). Health supervision of children with Down syndrome. *Pediatrics, 107*(2), 442-449.

Aruin, A.S., Almeida, G.L., & Latash, M.L. (1996). Organization of a simple two-joint synergy in individuals with Down syndrome. *American Journal of Mental Retardation, 101*(3), 256-268.

Baumeister, A.A., & Kellas, G. (1968). Reaction time and mental retardation. In N.R. Ellis (Ed.), *International review of research in mental retardation,* (vol. 2, pp. 163-192). New York: Academic Press.

Bauby, C.E., & Kuo, A.D. (2000). Active control of lateral balance in human walking. *Journal of Biomechanics, 33,* 1433-1440.

Bhambhani, Y., & Singh, M. (1985). Metabolic and cinematographic analysis of walking and running in men and women. *Medicine and Science in Sports and Exercise, 17*(1), 131-137.

Brooks, G.A., Fahey, T.D., White, T.P., & Baldwin, K.M. (1999). *Exercise Physiology: Human Bioenergetics and Its Applications.* Boston: McGraw Hill.

Browning, R.C., Baker, E.A., Herron, J.A. & Kram, R. (2005). Effects of obesity and sex on the energetic cost and preferred speed of walking. *Journal of Applied Physiology, 100,* 390-398.

Bruininks, R.H. (1974). Physical and motor development of retarded persons. In N.R. Ellis (Ed.) *International review of research in mental retardation,* (vol. 7, pp. 209-261). New York: Academic Press.

Buzzi, U.H., & Ulrich, B.D. (2004). Dynamic stability of gait cycles as a function of speed and system constraints. *Motor Control, 8,* 241-254.

Charteris, J., & Taves, C. (1978). The process of habituation to treadmill walking: a kinematic analysis. *Perceptual and Motor Skills, 47,* 659-666.

Chou, L., Kaufman, K.R., Hahn, M.E., Brey, R.H. (2003). Medio-lateral motion of the center of mass during obstacle crossing distinguishes elderly individuals with imbalance. *Gait and Posture, 18,* 125-133.

Cavanagh, P.R., & Kram, R. (1985). The efficiency of human movement – a statement of the problem. *Medicine and Science in Sports and Exercise, 17*(3), 304-308.

Cioni, M., Cocilovo, A., Rossi, F., Paci, D., & Valle, M.S. (2001). Analysis of ankle kinetics during walking in individuals with Down syndrome. *American Journal of Mental Retardation, 106*(5), 470-478.

Davis, W.E., & van Emmerik R.E.A. (1995). An ecological task analysis approach for understanding motor development in mental retardation: Philosophical and theoretical underpinnings. In M. Hebbelinck & R.J. Shephard (Series Eds.) & A. Vermeer & W.E. Davis (Vol. Eds.), *Medicine and sport science: Vol. 40. Physical and motor development in mental retardation* (pp. 1-32). Basel, Switzerland: Karger.

Dobbins, A.D., & Rarick, L.G. (1977). The performance of intellectually normal and educable mentally retarded boys on tests of throwing accuracy. *Journal of Motor Behavior*, *9*(1), 23-28.

Donelan, J.M., Kram, R., Kuo, A.D. (2001). Mechanical and metabolic determinants of the preferred step width in human walking. *Proceedings of the Royal Society of London B, 268,* 1985-1992.

Donelan, J.M., Shipman, D.W., Kram, R., Kuo, A.D. (2004). Mechanical and metabolic requirements for active lateral stabilization in human walking. *Journal of Biomechanics, 37,* 827-835.

Farley, C.T., & Ferris, D.P. (1998). In J.O. Holloszy (Ed.), *Exercise and Sports Science Reviews (Vol. 26, pp. 253-285).* Baltimore: Williams & Wilkins.

Fernhall, B., Pitetti, K.H., Rimmer, J.H., McCubbin, J.A., Rintala, P., Millar, A.L., et al. (1996). Cariorespiratory capacity of individuals with mental retardation including Down syndrome. *Medicine and Science in Sports and Exercise, 28*(3), 366-371.

Guerra Balic, M., Cuadrado Mateos, E., Geronimo Blasco, C., & Fernhall, B. (2000). Physical fitness levels of physically active and sedentary adults with Down syndrome. *Adapted Physical Activity Quarterly, 17,* 310-321.

Hamill, J., & Knutzen, K.M. (2003). *Biomechanical basis of human movement.* Baltimore: Lippincott Williams & Wilkins.

Heller, T., Hsieh, K., & Rimmer, J.H., (2004). Attitudinal and psychosocial outcomes of a fitness and health education program on adults with Down syndrome. *American Journal of Mental Retardation, 109*(2), 175-185.

Hoover, J.H., & Wade, M.G. (1985). Motor learning theory and mentally retarded individuals: a historical review. *Adapted Physical Activity Quarterly, 2,* 228-252.

Kubo, M., & Ulrich, B. (2006a). Coordination of the pelvis-HAT (head, arms and trunk) in anterior-posterior and medio-lateral directions during treadmill gait in preadolescents with/without Down syndrome. *Gait and Posture, 23,* 512-518.

Kubo, M., & Ulrich, B. (2006b). Early stage of walking: Development of control in medio-lateral and anteroposterior directions. *Journal of Motor Control, 38*(3), 229-237.

Kuo, A.D. (1999). Stabilization of lateral motion in passive dynamic walking. *International Journal of Robotics Research, 18,* 917-930.

Latash, M.L. (1993). *Control of human movement*. Champaign, IL: Human Kinetics.

Latash, M.L. (2000). Motor coordination in Down syndrome: The role of adaptive changes. In D.J. Weeks, R. Chua, & D. Elliott (Eds.), *Perceptual-motor behavior in Down syndrome (pp. 199-223).* Champaign, IL: Human Kinetics.

Latash, M.L., & Anson, J.G. (1996). What are "normal movements" in atypical populations? *Behavioral and Brain Sciences, 19,* 55-106.

Mahan, K.T., Diamond, E., & Brown, D. (1983). Podiatric profile of the Down's syndrome individual. *Journal of the American Podiatry Association, 73*(4), 173-179.

Margaria, R. (1976). *Biomechanics and energetic of muscular exercise.* Oxford: Clarendon Press.

McArdle, W.D., Katch F.I., & Katch, V.L. (2007). *Exercise physiology: Energy, nutrition, and human performance*. Baltimore: Lippincott Williams & Wilkins.

Melville, C.A., Cooper, S.-A., McGrother, C.W., Thorp, C.F., & Collacott, R. (2005). Obesity in adults with Down syndrome: A case control study. *Journal of Intellectual Disability Research, 49*(2), 125-133.

Newell, K.M. (1985). Motor skill acquisition and mental retardation: overview of traditional and current orientations. In J.E. Clark & J.H. Humphrey (Eds.), *Motor development: Current selected research* (pp. 183-192). Princeton, NJ: Princeton Books.

Newell, K.M. (1997). Motor skills and mental retardation. In W.E. MacLean, Jr. (Ed.), *Ellis' Handbook of mental deficiency: Psychological theory and research* (pp. 275-308). Mahwah, NJ: Erlbaum.

Newell, K.M., & Jordan, K. (2007). Task constraints and movement organization: A common language. In W.E. Davis & G.D. Broadhead (Eds.), *Ecological Task Analysis and Movement* (pp. 5-23). Champaign, IL: Human Kinetics.

Ohwada, H., Nakayama, T., Suzuki, Y., Yokoyama, T. & Ishimaru, M. (2005). Energy expenditure in males with mental retardation. *Journal of Nutritional Science and Vitaminology, 51,* 68-74.

Ounpuu, S. (1994). The biomechanics of walking and running. *Clinics in Sports Medicine, 13(4),* 843-863.

Parker, A.W., & Bronks, R. (1980). Gait of children with Down syndrome. *Archives of Physical Medicine and Rehabilitation, 61,* 345-351.

Pate, R.R., Pratt, M., Blair, S.N., Haskell, W.L., Macera, C.A., Bouchard, C., et al. (1995). Physical activity and public health. A recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. *JAMA, 273*(5), 402-407.

Pitetti, K.H., Climstein, M., Campbell, K.D., Barrett, P.J., & Jackson, J.A. (1992). The cardiovascular capacities of adults with Down syndrome: A comparative study. *Medicine and Science in Sports and Exercise, 24*(1), 13-19.

Ralston, H.J. (1958). Energy-speed relation and optimal speed during level walking. *Int. Z. angew. Physiol.*, 17, 277-288.

Rarick, G.L. (1973). Motor performance of mentally retarded children. In G.L. Rarick (Ed.), *Physical activity: Human growth and development* (pp. 225-256). New York: Academic Press.

Rimmer, J.H., & Yamaki, K. (2006). Obesity and intellectual disability. *Mental Retardation and Developmental Disabilities Research Reviews, 12,* 22-27.

Rimmer, J.H., Heller, T., Wang, E., & Valerio, I. (2004). Improvements in physical fitness in adults with Down syndrome. *American Journal of Mental Retardation, 109*(2), 165-174.

Roizen, N.J. (2002). Down syndrome. In M.L. Batshaw (Ed.), *Children with disabilities (pp. 307-320).* Baltimore: Paul H. Brooks.

Saunders, J.B.D., Inman, V.T. & Eberhart, H.D. (1953). The major determinants in normal and pathological gait. *Journal of Bone and Joint Surgery, 35-A*(3), 543-558.

Sparrow, W.A. (1983). The efficiency of skilled performance. *Journal of Motor Behavior, 15*(3), 237-261.

Sparrow, W.A., & Newell, K.M. (1998). Metabolic energy expenditure and the regulation of movement economy. *Psychonomic Bulletin & Review, 5*(2), 173-196.

Sparrow, W.A., & Day, R.H. (2002). Perception and action in mental retardation. In L.M. Glidden (Ed.), *International review of research in mental retardation* (pp. 241-278). San Diego, CA: Academic Press.

Stanish, H.I., Temple, V.A., & Frey, G.C. (2006). Health-promoting physical activity of adults with mental retardation. *Mental Retardation and Developmental Disabilities Research Reviews, 12,* 13-21.

Sutherland, G., Couch, M.A., & Iacono, T. (2002). Health issues for adults with developmental disability. *Research in Developmental Disabilities, 23,* 422-445.

Tsimaras, V., Giagazoglou, P., Fotiadou, E., Christoulas, K., & Angelopoulou, N. (2003). Jog-walk training in cardiorespiratory fitness of adults with Down syndrome. *Perceptual and Motor Skills, 96,* 1239-1251.

Ulrich, B.D., Haehl, V., Buzzi, U.H., Kubo, M., & Holt, K.G. (2004). Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Human Movement Science, 23,* 133-156.

U.S. Department of Health and Human Services (2000). Healthy people 2010: Understanding and improving health. Washington, DC: U.S. Government Printing Office.

U.S. Department of Health and Human Services (2002). *Closing the gap: A national blueprint to improve the health of persons with mental retardation.* Report of the Surgeon General's Conference on Health Disparities and Mental Retardation. Retrieved January 2, 2007, from http://www.specialolympics.org.

Wade, M.G., Newell, K.M., & Wallace, S.A. (1978). Decision time and movement time as a function of response complexity in retarded persons. *American Journal of Mental Deficiency, 83*(2), 135-144.

Whipp, B.J., & Wasserman, K. (1969). Efficiency of muscular work. *Journal of Applied Physiology, 26*(5), 644-648.

Winter, D.A. (2005). Biomechanics and motor control of human movement. Hoboken, NJ: John Wiley & Sons.

Yang, Q., Rasmussen, S.A., & Friedman, J.M. (2002). Mortality associated with Down's syndrome in the USA from 1983 to 1997: A population based study. *Lancet, 359,* 1019-1025.

APPENDICES

Appendix A. Literature Review

Efficiency of Walking in Persons with Down Syndrome

Stamatis Agiovlasitis

Persons with Down syndrome (DS) exhibit a preference for slow movement speeds (Davis & van Emmerik, 1995; Latash, 1993, 2000). Research has demonstrated that the time taken to respond to a stimulus (reaction time) and the time to complete a movement skill (movement time) are both slower in this population (Latash, 1993, 2000). Moreover, individuals with DS are anecdotally considered to be slow walkers. One explanation for this may lie in the efficiency of movement in these individuals. Simply stated, if persons with DS are less efficient when walking than persons without DS, then they may be choosing slower walking speeds in order to save energy. Alternatively, they may be walking slower in an attempt to ensure safety.

Physiological data regarding the efficiency of walking in persons with DS are lacking. However, several researchers have argued that the kinematics and kinetics of gait in these individuals are suggestive of inefficiency (Buzzi & Ulrich, 2004; Parker & Bronks, 1980; Ulrich et al., 2004). This is generally thought to result from attributes unique to persons with this condition. These are muscle hypotonia, increased joint laxity, pes planus (flat feet), cognitive limitations, decreased kinesthetic perception, increased visual abnormalities, and delayed motor development (Latash, 1993, 2000; Newell, 1997; Sparrow & Day, 2002).

This paper is divided into three sections. The first deals with definitions of efficiency of movement. This appears necessary since many different definitions have appeared in the physiological and biomechanical literature. The second section presents findings on the biomechanics of walking in persons with DS. Empirical information in this area suggests that these individuals may be less efficient that individuals without DS when walking. The last part examines possible causes of inefficient movement in persons with DS. This discussion follows the categorization of Winter (2005).

Efficiency of Movement - Definitions

Some inconsistency regarding the definition of *efficiency* exists in the literature (Cavanagh & Kram, 1985; Winter, 2005). In essence, *efficiency* reflects the contrast between energy output and energy input (McArdle, Katch, & Katch, 2001). It can be given by the ratio of the mechanical work done by all muscles to the metabolic work

of all muscles (Winter, 2005). However, as Winter (2005) noted, this definition is impractical because it is not possible to calculate the work done by each muscle during movement. Therefore, he proposed that *mechanical efficiency* should be calculated as the ratio of total mechanical work *(external + internal)* to the net metabolic cost *(total metabolic cost – resting metabolic rate)*. Still, the calculation of internal mechanical work is troublesome. For this reason, researchers have suggested a further modification by neglecting internal mechanical work (Winter, 2005). Although this approach is simpler, confusion remains as to the most appropriate denominator in the efficiency formula.

Gross efficiency, the ratio of external work to the total metabolic cost as measured by expired gas analysis has been proposed as an appropriate measure of efficiency (Stainsby, Gladden, Barclay, & Wilson, 1980). However, as Cavanagh and Kram (1985) pointed out, reported gross efficiencies range from -120% (for downhill treadmill walking) to +250% (for level treadmill walking). It is therefore apparent that this calculation is problematic. *Net efficiency*, on the other hand, is calculated by subtracting the resting metabolic rate from the total metabolic cost *(external work / total metabolic cost – resting metabolic rate)*. Moreover, in the calculation of *work efficiency*, the zero-work metabolic cost (e.g. for cycling, the energy required to pedal at zero work) is subtracted from total energy expenditure in the denominator (Cavanagh & Kram, 1985; Gaesser & Brooks, 1975; Winter, 2005). Gaesser and Brooks (1975) also proposed the use of *delta efficiency*, which is given by the following formula: *delta W / delta E* x 100, where *delta W* is the work production difference between two exercise intensities, and *delta E* is the respective energy expenditure difference between the two exercise levels. However, the validity of these baseline subtractions is questionable (Cavanagh & Kram, 1985; Stainsby et al., 1980). To complicate matters, the body performs no external work during horizontal walking and running, resulting in a numerator of zero. Therefore, the above calculations become impractical when evaluating the efficiency of locomotion. Brooks, Fahey, White, and Baldwin (1999) demonstrated the use of weights in an attempt to measure the efficiency of horizontal running on the treadmill. An alternative is to use an incline during treadmill locomotion (McArdle, Katch, &Katch, 2001). In both of these cases,

external work is performed by the body and efficiency can be calculated (Brooks et al., 1999; McArdle, Katch, & Katch, 2001). Regardless of the difficulties in the calculation of efficiency, McArdle, Katch, and Katch (2001) in reviewing the literature argued that the average efficiency for stationary cycling, walking, and running ranges between 20 and 25%.

Cavanagh and Kram (1985) contended that the above terms should not be confused with *muscle efficiency*. *Muscle efficiency* reflects the percent of energy available in foodstuffs that is converted to muscular work (Whipp & Wasserman, 1969). It is the product of *phosphorylation coupling efficiency* and *contraction coupling efficiency* (Cavanagh & Kram, 1985; Whipp & Wasserman, 1969). Because the former is 60% and the latter 49%, it follows that muscle efficiency is about 29%. In other words, the energy available in macronutrients can theoretically be converted to tension with an efficiency of 29%. The fact that the empirically determined average efficiency (20-25%) is similar to this value is not considered to have any physiological basis (Cavanagh & Kram, 1985; Stainsby et al., 1980).

Movement economy, on the other hand, refers to the relative oxygen uptake (mL/kg/min) at a given workload or velocity under steady-rate conditions (McArdle, Katch, & Katch, 2001). It is a more practical measure of the "ease of movement" that contributes substantially to endurance performance (McArdle, Katch, & Katch, 2001). When evaluating differences between people in the economy of locomotion, one needs to consider that walking and running velocity is not a reliable index of the work done (Cavanagh & Kram, 1985). Moreover, economy is sensitive to differences in muscle and joint architecture between persons (Cavanagh & Kram, 1985).

Efficiency has been considered an essential element in the definition of skilled performance, which is characterized by the development of forces that act in the optimal direction of movement (Cavanagh & Kram, 1985; Sparrow, 1983). However, even in elite cyclists only about 76% of the force developed in propulsion is actually used to produce work, rendering the coupling of the cyclist to the ergometer an inefficient phenomenon (Cavanagh & Kram, 1985). The remainder work produced by the cyclist is not converted to mechanical work. Whipp and Wasserman (1969) coined the term *motor efficiency* to reflect "the actual work output in performing a motor

task" and asserted that "if more skillful performance decreases the work required to perform a motor task, motor efficiency has increased" (p. 647). Sparrow (1983) argued that, with practice, novice performers refine their movements and achieve task goals by producing less work.

As it was mentioned earlier, the body does not produce any external work in walking. It is therefore difficult to quantify the physiological and motor efficiency of level walking in persons with varying characteristics. However, one may get an insight into the efficiency of walking by visualizing the movements of the body's center of mass (COM) throughout the gait cycle as proposed by the early work of Saunders, Inman, and Eberhart (1953). This group theorized that, in walking, the phasing of joint kinematics allows COM to follow a smooth sinusoidal curve in the plane of progression. This way, rapid and pronounced displacements of COM are avoided resulting in a gait pattern that is the most economical for humans. These researchers proposed six mechanisms through which the three-dimensional translation of the COM in normal gait becomes smoother compared to a hypothetical compass-type gait: a) pelvic rotation, b) pelvic tilt, c) knee flexion in stance, d) foot mechanism (rapid plantar flexion) in conjunction with e) initiation of knee flexion during push off, and f) lateral displacement of the pelvis. It was argued that, collectively, these mechanisms act to produce a smooth sinusoidal pathway of the COM with minimal vertical and medio-lateral displacements during the gait cycle. In this way, the amount of energy exchanged between the potential energy and kinetic energy of the COM remains at minimal levels, resulting in the lowest energy cost. Saunders, Inman, and Eberhart (1953) argued that this pattern develops with practice in growing children. They also proposed that if one of the kinematic mechanisms described above is malfunctioning as in disability, then another will become more pronounced to compensate for the loss. Although this possibility applies to the gait of individuals with DS, it has not been tested empirically.

Biomechanics of gait in Down syndrome

The kinematics and kinetics of gait in persons with DS, particularly of adults, have not been studied extensively. Two early studies investigated the kinematic

characteristics of gait in seven- and five-years-old children with DS (Parker & Bronks, 1980; Parker, Bronks, & Snyder, 1986). Collectively, the children with DS in these investigations had shorter step length than their peers, owing to their shorter leg length. They seemed to spend more time in double-support, a finding that Parker, Bronks, and Snyder (1986) interpreted as an indication of reduced gait stability. Sagittal plane angular displacements at the hip, knee, and ankle were reduced, compared to normative values for children and adults without DS. Five-year-old children with DS showed greater hip flexion throughout the gait cycle and increased knee flexion during the support phase, findings attributed to a possible attempt to lower their COM and compensate for instability (Parker, Bronks, & Snyder, 1986). The most pronounced differences were observed at the ankle. At initial contact, children with DS approached the ground with their ankle plantar-flexed (foot flat). At toe-off, they demonstrated substantially less plantar-flexion. Moreover, the timing of kinematic changes in direction at the ankle was different (delayed). In addition, increased variability in ankle kinematics during the cycle was observed. The researchers argued that this was suggestive of poor neuromuscular control and, possibly, muscular weakness at this joint. In the frontal plane, seven-year-old children with DS showed greater hip abduction during the swing phase, an observation that was attributed to an attempt to allow for foot clearance (Parker & Bronks, 1980). Furthermore, the researchers detected consistent out-toeing in response to exaggerated lateral displacements and the need for a wider base of support. The authors concluded that these kinematic characteristics were suggestive of an inefficient gait pattern. It should be emphasized, however, that both of these studies did not incorporate a control group.

In contrast, Cioni, Cocilovo, Rossi, Paci, and Valle (2001) did include a control group in a study that attempted to evaluate sagittal gait kinematics and kinetics at the ankle of 17 persons with DS ranging in age from 8- to 36-years-old. All participants in the experimental group were clinically diagnosed with hypotonia, ligament laxity, flat feet, and ankle valgus. The gait velocities studied ranged from 0.6 to 1.2 m/s. In agreement with the previous investigations outlined above, the average ankle angular displacement in persons with DS was decreased compared to their peers.

The initial contact of these persons was with the foot somewhat plantar-flexed. During the mid-terminal stance phase, participants with DS had considerably greater variability for dorsi-flexion than their counterparts. When walking at 0.95 and 0.96 m/s, they demonstrated reduced power absorption with two peaks during loading response and mid-stance. Two explanations were offered for this phenomenon: first, a tight Achilles tendon due to plantar-flexion and ligament instability, and second, possible abnormalities in the visco-elastic properties of hypotonic muscles. Moreover, participants with DS exhibited lower ankle-flexor moment and power generation in terminal stance and pre-swing, compared to the control group. The researchers argued that this may be caused by the reduced energy absorption during stance and by possible weakness of the plantar flexors. At slower walking velocities, a prolonged phase of power generation was observed until the pre-swing. This finding was explained as an attempt to facilitate a stable base of support on the contra-lateral foot.

However, Ulrich, Haehl, Buzzi, Kubo, and Holt (2004) found that sagittal plane kinematics of over-ground walking for the thigh, shank, and foot of pre-adolescents with DS did not show significant differences from those of their peers with typical development (TD). During over-ground walking at the preferred speed, pre-adolescents with DS did not demonstrate any differences in spatio-temporal variables, with the exception of wider step widths. When asked to walk on a treadmill, on the other hand, these children displayed higher stride frequencies and shorter stride lengths than their controls across a variety of speeds. These researchers also used a damped inverted pendulum and spring model with an escapement function to contrast the global stiffness and forcing between the groups. Their results indicated that stiffness was not different between the groups when walking over-ground. When walking on the treadmill, children with DS showed higher levels of stiffness across all speeds. It was therefore proposed that, when the gait of these children is perturbed as during treadmill locomotion, stiffness increases perhaps by co-contraction of antagonistic muscle groups in an attempt to optimize stability rather than metabolic efficiency. Moreover, the children with DS demonstrated higher levels of angular impulse on the treadmill. This finding was explained as an effort to overcome the increased stiffness and maintain an optimal stride length. The researchers also argued

that higher angular impulse may be needed to overcome increased losses of energy during the gait cycle. Children with DS, they suggested, may be prone to reduced energy storage and return because of their characteristic pes planus and because of their excessive medio-lateral movements.

Using a similar set of participants, Buzzi and Ulrich (2004) compared the dynamic stability in the lower extremity of children with DS to that of children with TD across a series of treadmill walking speeds. Using tools from non-linear dynamics (maximum Lyapunov exponents and approximate entropy), these investigators found that participants with DS had reduced dynamic stability than their peers at the thigh, shank, and foot. However, stability at the shank and foot of children with DS improved with increasing speeds. The authors concluded that the children with DS exhibited greater dynamic instability, attributed to the clinical manifestations of their syndrome, namely, joint laxity, hypotonic muscles, and deficits in motor-control processes.

Collectively, the above review demonstrates that the gait of persons with DS may be less efficient than that of persons without this condition, particularly in unpredictable environments.

Causes of inefficient movement in Down syndrome

The following discussion draws largely on the presentation by Winter (2005), who outlined four major causes of mechanical inefficiency: a) co-contractions, b) isometric contractions against gravity, c) generation of energy at one joint and absorption at the other, and d) jerky movements. An overview of these phenomena with special reference to DS appears below.

Co-contraction refers to the simultaneous contraction of antagonistic muscles. In this scheme, the work produced by the agonist is opposed by the work produced by the antagonist. This results in unnecessary positive work by the agonist that is not producing any net movement. In the absence of the opposing work by the antagonistic muscle groups, the same net effect may be accomplished by less positive work. Co-contraction is a common characteristic of pathology, as in the gait of children with cerebral palsy. It is also a feature that promotes ankle-joint stabilization in non-pathological walking (Winter, 2005). This phenomenon may be exaggerated in the gait

of persons with DS, who are characterized by joint laxity. As previously mentioned, it has been proposed that, when walking on the treadmill, children with DS may co-contract their muscles in order to achieve an optimal and more stable stride length (Ulrich et al, 2004). Furthermore, individuals with DS seem to favor a co-contraction strategy during single-joint movements (Aruin, Almeida, & Latash, 1996) and when attempting to deal with perturbations (Latash, Almeida, & Corcos, 1993). Experimental evidence of co-contraction during gait in persons with DS is lacking. However, Ulrich et al. (2004) argued that co-contraction may be a universally preferred strategy by these individuals when attempting to deal with the effects of perturbation, as in treadmill locomotion.

As Winter (2005) explained, isometric contractions against gravity occur when there is a need to hold limb segments momentarily (isometrically). During isometric action, there is no work produced, but this comes at an expense of energy which affects the denominator in the efficiency formula. Isometric contractions against gravity do not occur to a great extent during normal movement, when there is a smooth exchange of energy between segments (Winter, 2005). This phenomenon, however, becomes a significant contributor of inefficiency during pathological gait, especially when walking at slow speeds. Winter (2005) illustrated the example of a child with cerebral palsy who holds her leg in knee flexion for an extended period of time during the swing phase while walking with crutches. A valid technique for the quantification of isometric contractions against gravity awaits development (Winter, 2005). Consequently, there is no empirical information regarding the presence of this phenomenon in the gait of persons with or without DS. It is known, however, that persons with DS have a preference for slow movements (Latash, 1993, 2000).

Generation of energy at one joint and absorption at the other may also contribute to inefficient movement. This occurs when the positive work at one joint is opposed by negative work at other joints (Winter, 2005). Winter contended that this phenomenon is present normally during the gait cycle. The positive (concentric) work by the plantar-flexors in push-off is opposed by the negative (eccentric) work performed by the quadriceps and tibialis anterior of the opposite leg during weight acceptance. Winter (2005) argued that gait instability associated with certain

pathologies enhances the presence of this phenomenon and causes inefficiency. As reviewed in the previous section, children and adults with Down syndrome are considered to possess characteristics that make them unstable during walking. Evidence of instability during gait in persons comes from studies that have investigated kinematic and kinetic variables (Cioni et al., 2001; Parker & Bronks, 1980; Parker et al., 1986; Ulrich et al., 2004). Moreover, Buzzi and Ulrich (2004), who used tools from non-linear dynamics, found greater dynamic instability during treadmill locomotion in children with DS. Often, researchers refer to the gait of these persons as being "wobbling" (Buzzi & Ulrich, 2004; Ulrich et al., 2004). It should also be remembered from the previous section that power generation and power absorption at the ankle during stance in the walking of persons with DS are lower than those of persons without DS (Cioni et al., 2001). The extent to which generation of energy at one joint and absorption at the other during gait is greater in individuals with DS compared to individuals without DS, awaits experimental testing.

Efficient movements are smooth-looking (Winter, 2005). In contrast, pathologic movement is often a succession of stops and starts (i.e. acceleration does not remain constant). When this happens, the energy added to the body by positive work is removed by negative work, yielding a metabolic cost (Winter, 2005). Jerky movements are obvious in the child with cerebral palsy. Evidence regarding the acceleration of movements in individuals with DS is lacking. However, these persons are characterized as "clumsy" (Davis & van Emmerik, 1995). Although a clear definition of "clumsiness" is lacking, it may be thought of as sharing some common ground with jerky movements. The possibility that this factor of inefficiency is present in the gait of persons with DS can be examined by an analysis of joint powers or an evaluation of the energy exchange between segments (Winter, 2005).

In reviewing the literature, Latash (2000) proposed a theory for the origin of "clumsiness" in persons with DS. His argument was based on some evidence showing that individuals with this condition have lower cerebellum weight. Abnormalities in the cerebellum may affect difficulties in the organization of synergies. This factor could then cause everyday tasks to be perceived as challenging, especially when a high degree of unpredictability is present. Therefore, these individuals may favor

safety and accuracy, which may be the cause of longer reaction times, slow movements, and co-contractions. The end result may be “clumsiness.”

In summary, it appears that the unique attributes of individuals with DS predispose them to being less efficient during walking than persons without DS. These attributes are joint laxity, muscle hypotonia, pes planus, decreased cerebellum weight, cognitive limitations, decreased kinesthetic perception, increased visual abnormalities, and delayed motor development. Persons with DS exhibit greater medio-lateral movements during the gait cycle. Their capability for energy storage and return at the ankle is inferior to those without DS. These characteristics may affect their efficiency during walking. In addition, they seem to possess several of the causes of inefficient movement, particularly co-contractions. Co-contraction of antagonistic muscles appears to be a somewhat universal strategy when these individuals are coping with perturbations. One should be cautioned that most of the studies reviewed here used treadmill and not over-ground locomotion. It is unclear to what extent the causes of inefficiency are present when persons with DS walk over-ground. Nevertheless, it is evident that there is a need for physiological data to substantiate claims for inefficient walking in individuals with this genetic syndrome.

References

Aruin, A.S., Almeida, G.L., & Latash, M.L. (1996). Organization of a simple two joint synergy in individuals with Down syndrome. *American Journal of Mental Retardation, 101*(3), 256-268.

Brooks, G.A., Fahey, T.D., White, T.P., & Baldwin, K.M. (1999). *Exercise Physiology: Human Bioenergetics and Its Applications.* Boston: McGraw Hill.

Buzzi, U.H., & Ulrich, B.D. (2004). Dynamic stability of gait cycles as a function of speed and system constraints. *Motor Control, 8,* 241-254.

Cavanagh, P.R., & Kram, R. (1985). The efficiency of human movement – a statement of the problem. *Medicine and Science in Sports and Exercise, 17*(3), 304-308.

Cioni, M., Cocilovo, A., Rossi, F., Paci, D., & Valle, M.S. (2001). Analysis of ankle kinetics during walking in individuals with Down syndrome. *American Journal of Mental Retardation, 106*(5), 470-478.

Davis, W.E., & van Emmerik R.E.A. (1995). An ecological task analysis approach for understanding motor development in mental retardation: Philosophical and theoretical underpinnings. In M. Hebbelinck & R.J. Shephard (Series Eds.) & A. Vermeer & W.E. Davis (Vol. Eds.), *Medicine and sport science: Vol. 40. Physical and motor development in mental retardation* (pp. 1-32). Basel, Switzerland: Karger.

Gaesser, G.A., & Brooks, G.A. (1975). Muscular efficiency during steady-rate exercise: effects of speed and work rate. *Journal of Applied Physiology, 38*(6), 1132-1139.

Latash, M.L. (1993). *Control of human movement*. Champaign, IL: Human Kinetics.

Latash, M.L. (2000). Motor coordination in Down syndrome: The role of adaptive changes. In D.J. Weeks, R. Chua, & D. Elliott (Eds.), *Perceptual-motor behavior in Down syndrome (pp. 199-223).* Champaign, IL: Human Kinetics.

Latash, M.L., Almeida, G., & Corcos, D.M. (1993). Preprogrammed reactions in individuals with Down syndrome: The effects of instruction and predictability of the perturbation. *Archives of Physical Medicine and Rehabilitation, 74,* 391-399.

McArdle, W.D., Katch F.I., & Katch, V.L. (2001) *Exercise physiology: Energy, nutrition, and human performance*. Baltimore: Lippincott Williams & Wilkins.

Newell, K.M. (1997). Motor skills and mental retardation. In W.E. MacLean, Jr. (Ed.), *Ellis' Handbook of mental deficiency: Psychological theory and research* (pp. 275-308). Mahwah, NJ: Erlbaum.

Parker and Bronks (1980). Gait of children with Down syndrome. *Archives of Physical Medicine and Rehabilitation, 61,* 345-351.

Parker, Bronks, & Snyder, (1986). Walking patterns in Down's syndrome. *Journal of Mental Deficiency Research, 30,* 317-330.

Saunders, J.B.D., Inman, V.T. & Eberhart, H.D. (1953). The major determinants in normal and pathological gait. *Journal of Bone and Joint Surgery, 35-A*(3), 543-558.

Sparrow, W.A. (1983). The efficiency of skilled performance. *Journal of Motor Behavior, 15*(3), 237-261.

Sparrow, W.A., & Day, R.H. (2002). Perception and action in mental retardation. In L.M. Glidden (Ed.), *International review of research in mental retardation* (pp. 241-278). San Diego, CA: Academic Press.

Stainsby, W.N., Gladden, Barclay, L.B., & Wilson, B.A. (1980). Exercise efficiency: validity of base-line subtractions. *Journal of Applied Physiology, 48*(3), 518-522.

Ulrich, B.D., Haehl, V., Buzzi, U.H., Kubo, M., & Holt, K.G. (2004). Modeling dynamic resource utilization in populations with unique constraints: Preadolescents with and without Down syndrome. *Human Movement Science, 23,* 133-156.

Whipp, B.J., & Wasserman, K. (1969). Efficiency of muscular work. *Journal of Applied Physiology, 26*(5), 644-648.

Winter, D.A. (2005). Biomechanics and motor control of human movement. Hoboken, NJ: John Wiley & Sons.

Appendix B. Health History Questionnaire

Health History Questionnaire

Participant I.D. #: _____

Name: _____ Date: ___/___/___

Date of Birth: ___/___/___ Age: _____ Sex: _____

- **Please mark the appropriate box with an X**
- **If you have any questions regarding specific items, please ask the researcher for clarification**

	Question	**YES**	**NO**	**Don't Know**
1	Has your doctor ever said that you should **only** do physical activity as recommended by a doctor?			
2	Has your doctor ever said that you have a heart condition? If yes, what exactly? _____ How is it treated? _____			
3	Have you ever had a heart attack?			
4	Do you feel pain in your chest when **you do** physical activity?			
5	In the past month, have you had chest pain when you were **not** doing physical activity?			
6	Do you lose your balance because of dizziness?			
7	Do you ever lose consciousness?			
8	Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?			
9	Are you currently taking any medications? If so, list them: _____ For what conditions are you taking these medications? _____			

	Question	**YES**	**NO**	**Don't Know**
10	Do you have diabetes? If so, list medications taken: _____			
11	Do you have any orthopedic or musculoskeletal problems? (joint, bone, muscle disease/pain) If yes, what exactly? _____ How is it treated? _____ List medications taken for the condition: _____			
12	If "yes" to the previous question, could this problem be made worse by a change in your physical activity?			
13	Have you ever used braces, orthotics or special shoes? If yes, what exactly? _____			
14	Do you have any neurological diseases? If yes, what exactly? _____ How is it treated? _____ List medications taken for the condition: _____			
15	Do you have asthma?			
16	Do you feel shortness of breath at rest?			
17	Do you feel shortness of breath at when you do physical activity?			
18	Do you have any pulmonary/lung diseases? If yes, what exactly? _____ How is it treated? _____ List medications taken for the condition: _____			
19	Do you have any other physical disability? If yes, what exactly? _____ How is it treated? _____ List medications taken for the condition:_____			
20	Do you know of any other reason why you should not do physical activity? If so, what exactly? _____			

	Question	**YES**	**NO**	**Don't Know**
21	Are you pregnant?			
22	Do you suspect that you may be pregnant?			
23	Are you physically active? If yes, what type(s) of activity do you perform regularly? _____			
24	How often do you perform physical activity? _____ times per week			
25	For how long do you perform physical activity? _____ minutes			
26	Do you like to walk?			
27	How often do you walk? _____ times per week			
28	Approximately how many minutes do you walk every day? _____ minutes			
29	Where do you walk? (indoor or outdoor track, trails, sidewalk, treadmill) _____			
30	What is the speed of your walks? Circle one: Slow Moderate Fast			
31	Do you fall when walking? If yes, how often? _____			
32	Do you trip when walking? If yes, how often? _____			
33	Have you ever used a treadmill? If so, when was the last time you used it? _____			
34	Do you currently use a treadmill? If yes, how often do you use it? _____ times per week Where do you use the treadmill? Circle one: home health club			

Continued on next page

Please provide us with emergency contact information

Name: _____ Home Phone: _____

Relation: _____ Work Phone: _____

The following section is filled by the researchers

Can the participant be included in the study? _____
Explain:
_____
_____
_____
_____
_____
_____

Should the participant be withdrawn from the study? _____
Explain:
_____
_____
_____
_____
_____
_____