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The aging human neuromuscular system expresses less certainty for selecting joint kinematics during gait

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Abstract

This investigation quantitatively characterized the certainty of the aging neuromuscular system in selecting a joint range of motion during gait based on the statistical concept of entropy. Elderly and young control groups walked on a treadmill at a self-selected pace. Joint angles were calculated for the ankle, knee and hip. We hypothesized that the aging group would exhibit less certainty in selecting a joint range of motion during gait. Our results supported this hypothesis, and indicated that aged individuals demonstrated statistically less certainty for the knee (16.8%) and hip (24.6%). We suggest that neurophysiological changes associated with aging may result in less certainty of the neuromuscular system in selecting a stable gait.

Keywords: Variability; Entropy; Elderly; Gait; Locomotion; Nonlinear dynamics

Several investigations have indicated that the circuitry of the nervous system is organized into a collection of neuronal groups and pathways that share functional properties, and fire in a temporally correlated fashion [1,4,17,19]. It has been suggested that slight variations in the firing patterns of the neural circuitry allow the nervous system to experimentally develop new ways to organize [17]. Thus, variability in the firing of the neural circuitry is necessary for the organization of the nervous system [17,19]. Neural circuitry that tends to produce successful outcomes is strengthened and has a higher probability of being used again for similar tasks. Conversely, selected neural circuitry that is unsuccessful is weakened and has a lower probability of being used again [17,19].

Methods such as statistical entropy have previously been used to evaluate the neural circuitry involved in brain behavior [15,19]. Statistical entropy is a measure from the concepts of information theory. It quantifies the variation in a bio-signal that is defined based on the probability distribution of observed events [19]. Bio-signals that have a higher probability of repeating their behavior over time have a low amount of entropy. Alternatively, a random distribution in the behavior of the bio-signal over time has a high amount of entropy. Based on this notion, a low amount of entropy indicates less noise or uncertainty in the behavior of the bio-signal as time progresses [19]. Thus, statistical entropy can be used to explain the certainty of the central nervous system for selecting neural circuitry that will meet the demands of a given task. A low amount of entropy indicates greater certainty that the selected neural circuitry will meet the constraint of the given task. Conversely, a high amount of entropy indicates less certainty that the selected neural circuitry will meet the constraints of the given task.

Investigations of human movement have noted variability in the lower extremity movement patterns during gait [3,5-7,12]. Such variability may be due to the fact that more than one neural pathway can be used to perform the same lower extremity movement pattern [17]. Theoretically, the lower extremity joint kinematics are global expressions of the behavior of the neuromuscular system. Based on this, the global certainty of the neuromuscular system for selecting neural pathways for gait can be explored through measures of joint kinematic entropy. A high entropy value for the joint kinematics may indicate that the neuromuscular system has less certainty for which pathways to use for gait. Alternatively, a low entropy value may indicate greater certainty in the neuromuscular system for selecting neural pathways.

Aging has been associated with characteristic changes in the lower extremity kinematic variability during gait [4, 6 – 8,14]. However, no investigations have considered if these changes in variability are related to the certainty of the neuromuscular system for finding a stable gait. It is well known that aging is associated with neurophysiological changes [2,9,14]. These changes may hinder the ability of the nervous system to appropriately select neural pathways for a stable and functional gait. Therefore, joint kinematics of the elderly during gait may be affected by less certainty. A less amount of certainty in selecting a stable gait may also be related to falls in the elderly.

In this investigation, we sought to quantitatively characterize the global certainty of the aging neuromuscular system during gait through lower extremity joint kinematics. To accomplish this goal we used the statistical concept of entropy to measure the certainty present in the lower extremity joint kinematics during gait. It was hypothesized that the aging neuromuscular system would have less certainty during gait. We speculated that less certainty may be due to neurophysiological changes associated with the aging neuromuscular system.

Participants of this investigation included young control (n = 10; age 25.1 ± 5.3 years) and elderly (n = 10; age 74.6 ± 2.5 years) subjects who had prior treadmill walking experience. The elderly subjects included in this investigation met the following criteria: independent ambulation (i.e. no assistive devices), independent living in the community, no neurological pathology, no acute illness, and no restrictions in activities of daily living. Screening of the elderly subjects for neuromuscular deficiencies was performed by a licensed physical therapist. Prior to testing, each subject read and signed an informed consent that was approved by the University Institutional Review Board.

The subjects walked on a treadmill, while kinematic data of the right lower extremity were collected using a 60 Hz high-speed video camera. Prior to videotaping, reflective markers were positioned on the subject's right lower extremity. All positional markers were placed on the subjects by the same examiner. Sagittal plane markers placement was as follows: (a) greater trochanter; (b) axis of the knee joint as defined by the alignment of the lateral condyles of the femur; (c) lateral malleolus; (d) outsole of the shoe approximately at the bottom of the calcaneus; and (e) outsole of the shoe approximately at the fifth metatarsal head.

The subjects were allowed to warm-up for a maximum of 8 min. During the warm-up session, each subject established a self-selected comfortable walking pace. Subjects were instructed to select a pace that would be similar to a pace they would use when performing continuous aerobic walking. Collection of data did not occur until subjects stated that they felt comfortable and could maintain the self-selected pace for a long duration. Once the subject felt comfortable walking on the treadmill, 15 consecutive gait cycles (trials) were collected per subject. The gait cycles were separated for analysis via custom laboratory software. With this software, the second derivative of the heel marker vertical displacement, along with visual inspection of the stick figure, was utilized to determine the respective heel contacts of the gait cycle.

Joint markers were digitized using Peak Performance Technologies' Motus System (Peak Performance Technologies, Inc., Englewood, CO). The obtained kinematic positional coordinates of the sagittal markers were scaled and smoothed using a Butterworth Lowpass Filter with a selective cutoff algorithm [8]. The cutoff frequency values used were 6 – 10 Hz. From the plane coordinates obtained, the sagittal foot, shank, and thigh angular displacements were calculated relative to the right horizontal axis. Calculation of the ankle, knee and hip joint angles was based on an absolute approach. The joint angular displacements were normalized to 100 points per gait cycle using a cubic spline routine. Subsequently, the range of motion (ROM) was determined from the absolute difference of the absolute maximum and absolute minimum for the ankle, knee, and hip joint angle curves (Fig. 1).

Entropy was used to measure the amount of certainty of the neuromuscular system for selecting a joint ROM during gait [15,19]. It was assumed that the joint ROM had a number of possible discrete states (i.e. ROM = 1, 2, …, m). Each of these states was associated with a probability (P_m) such that the sum of the probabilities for all the discrete states was equal to one. Eq. (1) expresses the probability of each discrete state:

$$P_m = |m|/|S| \tag{1}$$

where P_m is the discrete probability of a selected ROM, $|m|$ is the cardinality (number of times the ROM was repeated) of a discrete state, and $|S|$ is the cardinality of the total discrete states observed by the respective joint (i.e. all possible discrete states). Based on the calculated probabilities, the following equation was used to calculate the

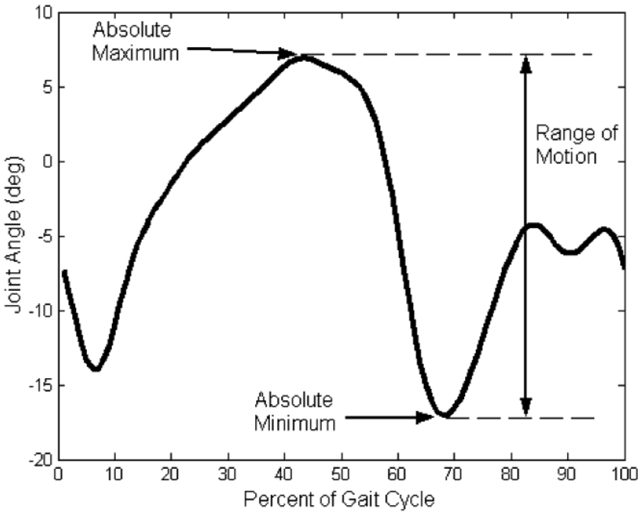

Fig. 1. Definition used for joint range of motion based on the absolute minimum and maximums.

statistical entropy ($H(X)$) of the joint (Eq. (2)) [15,19]:

$$H(X) = -\sum_{m=1}^{m} P_m \log_2(P_m) \qquad (2)$$

A small entropy value indicated greater certainty in selecting a joint ROM [15,19]. Conversely, if the entropy value was large there was less certainty in selecting a joint ROM. A Kolmogorov – Smirnov statistic test indicated that our data were normally distributed and that an independent t-test was an appropriate statistical measure to discern group differences in entropy at the respective joints. All statistical tests were conducted with an alpha level of 0.05.

Results of this investigation indicated that there were statistical differences ($P < 0.05$) in entropy for the knee and hip ROM of the two groups (Table 1). The larger entropy values indicated that there was less certainty in selecting a ROM for the knee and hip for the aging group. Although there was no significant difference between the two groups for the ankle ($P > 0.05$), it can be observed that the aging mean entropy value was still larger. Overall, the aged individuals demonstrated less certainty for the ankle (8.4%), knee (16.8%) and hip (24.6%).

The results of this investigation support our hypothesis that aging is associated with less certainty in the neuromuscular system for selecting joint kinematics during gait. It is possible that the less certainty may be due to neurophysiological changes associated with aging [2,9,14]. Such neurophysiological changes can result in inaccurate information from the visual, vestibular and somatosensory receptors (proprioceptive, cutaneous, and joint receptors) [2,14,20]. Previously it has been noted that inaccurate sensory information can result in a loss of stability in the elderly [20]. It is possible that neuromuscular certainty in selecting the appropriate kinematic behavior may be dependent on sensory feedback during gait. Thus, the aging neuromuscular system may not receive appropriate information to be certain that the selected kinematic behavior will provide a stable gait. Such uncertainty may be responsible for the increased probability of falls in the elderly. Further investigations are necessary to determine the relationship between sensory feedback and the lack of certainty in the elderly gait.

Recent investigations of brain behavior may provide additional support that sensory feedback may be necessary for neuromuscular certainty during gait. There is considerable scientific evidence that motor tasks have a neural

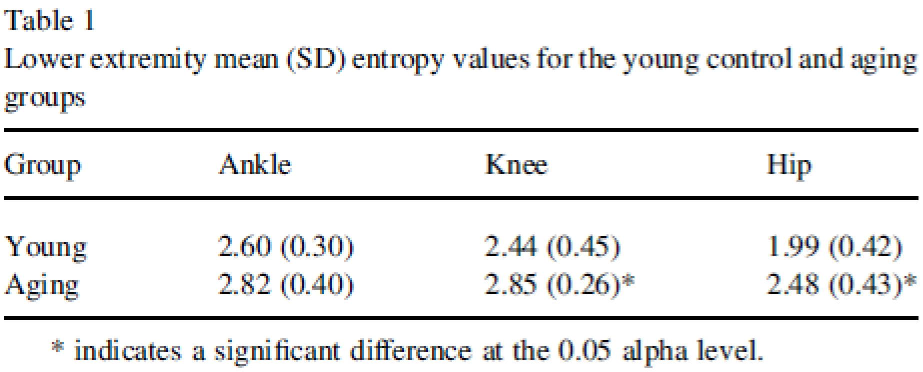

Table 1
Lower extremity mean (SD) entropy values for the young control and aging groups

Group	Ankle	Knee	Hip
Young	2.60 (0.30)	2.44 (0.45)	1.99 (0.42)
Aging	2.82 (0.40)	2.85 (0.26)*	2.48 (0.43)*

* indicates a significant difference at the 0.05 alpha level.

representation in the prefrontal cortex and cerebellum [10, 11,13,16]. These neural representations are dynamically created and adjusted to accommodate the ever-changing environmental stimulus [10,11,13]. It has been suggested that recursively using these neural constructs results in an increased likelihood that successful neuromuscular pathways will be selected over other possible pathways for a motor task [17]. Such recursive identification of successful neuromuscular pathways tends to integrate sensory feedback and motor areas of the brain that are responsible for movement patterns [17,18]. It is possible that the diminished capacity of the elderly neuromuscular system may result in the inability to discriminate and categorize sensory inputs that are correlated with successful motor processes. An inability to discriminate and categorize sensory inputs may be related to less certainty in the elderly kinematics noted in this investigation.

Prior investigations have noted changes in the variability for elderly gait [3,5 – 7,12]. However, no investigations have considered if these changes in variability may be related to certainty of the neuromuscular system for finding a stable gait. The use of statistical entropy in this investigation to explore the certainty expressed in joint kinematic fluctuations offers new insights on the control mechanisms of the neuromuscular system. Additionally, statistical entropy provides a meaningful interpretation of the variability seen in gait. Future research should attempt to elucidate the underlying reason for why the elderly display globally less certainty during gait. Such explorations should concentrate their efforts on determining how sensory information is related to the less certain gait patterns seen in the elderly. This information will provide a greater understanding of the neuromuscular system and may aide in prognostic and diagnostic measures of neuromuscular health.

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References

[1] S.L. Bressler, Large-scale cortical networks and cognition, Brain Res. Rev. 20 (1995) 288 – 304.

[2] L.J. Dorfman, T.M. Bosley, Age related changes in peripheral and central nerve conduction in man, Neurology 29 (1979) 38 – 44.

[3] A. Gabel, U.S.L. Nayak, The effect of age on variability in gait, J. Gerontol. 39 (1984) 662 – 666.

[4] C.M. Gray, W. Singer, Stimulus-specific neuronal oscillations in orientation columns of cat visual cortex, Proc. Natl. Acad. Sci. USA 86 (1989) 1698 – 1702.

[5] J.M. Hausdorff, D.E. Forman, Z. Ladin, A.L. Golderberger, D.R. Rigney, J.Y. Wei, Increased walking variability in elderly persons with congestive heart failure, J. Am. Geriatr. Soc. 42 (1994) 1056 – 1061.

[6] J.M. Hausdorff, H.K. Edelberg, S.L. Mitchell, A.L. Goldberger, Increased gait unsteadiness in community-dwelling elderly fallers, Arch. Phys. Med. Rehabil. 78 (1997) 278 – 283.

[7] J.M. Hausdorff, S.L. Mitchell, R. Firtion, C.K. Peng, M.E. Cudkowicz, J.Y. Wei, A.L. Goldberger, Altered fractal dynamics of gait: reduced stride-interval correlations with aging and Huntington’s disease, J. Appl. Phys. 78 (1997) 349 – 358.

[8] K.M. Jackson, Fitting of mathematical functions to biomechanical data, IEEE Trans. Biomed. Eng. 26 (1979) 515 – 521.

[9] G.S. Kamen, S.V. Sison, D.U. Duke, C. Patten, Motor unit discharge behavior in older adults during maximal effort contractions, J. Appl. Phys. 79 (1995) 1908 – 1913.

[10] J. Kleim, S. Barby, R.J. Nudo, Functional reorganization of the rat motor cortex following motor skill learning, J. Neurophysiol. 80 (1998) 3321 – 3325.

[11] J. Liepert, H. Bauder, W.H.R. Miltner, E. Taub, C. Weiller, Treatment-induced cortical reorganization after stroke in humans, Stroke 31 (2000) 1210 – 1216.

[12] B.E. Maki, Gait changes in older adults: predictors of falls or indicators of fear?, J. Am. Geriatr. Soc. 45 (1997) 313 – 320.

[13] R.J. Nudo, B.M. Wise, F. SiFuentes, G.W. Miliken, Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct, Science 272 (1996) 1791 – 1794.

[14] A.R. Potvin, K. Syndulko, W.W. Tourtellotte, J.A. Lemmon, J.H. Potvin, Human neurologic function and the aging process, J. Am. Geriatr. Soc. 28 (1980) 1 – 9.

[15] F. Rieke, Spikes: Exploring the Neural Code, MIT Press, Cambridge, MA, 1997.

[16] R. Shadmehr, H.H. Holcomb, Neural correlates of motor memory consolidation, Science 277 (1997) 821 – 825.

[17] O. Sporns, G.M. Edelman, Solving Bernstein’s problem: a proposal for the development of coordinated movement by selection, Child Dev. 64 (1993) 960 – 981.

[18] O. Sporns, J.A. Gally, G.N. Reeke, G.M. Edelman, Reentrant signaling among simulated neuronal groups leads to coherency in their oscillatory activity, Proc. Natl. Acad. Sci. USA 86 (1989) 7265 – 7269.

[19] G. Tononi, G.M. Edelman, O. Sporns, Complexity and coherency: integrating information in the brain, Trends Cogn. Sci. 2 (1998) 474 – 484.

[20] M.H. Woollacott, A. Sumway-Cook, L.M. Nashner, Aging and posture control: changes in sensory organization and muscular coordination, Int. J. Aging Hum. Dev. 23 (1986)97-114.