Quantifying Coordination of Human Gait: Fall Risk and Effects of Aging

by

Jacob F. Oeding

Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

Falls have become an immense source of physical, social, and economic hardship among older adults. Compromised coordination, defined as a decrease in the ability to properly time the motion of body segments with one another, is thought to be one factor contributing to the high rate of falls in older populations. Thus, coordination is often used by clinicians as a measure to help identify a patient's risk of falling, as well as by therapists to design targeted rehabilitative programs with the goal of reducing that fall risk. However, these assessments are currently evaluated subjectively, motivating the need for an objective measure of coordination. The aims of this study were to assess age-related differences in inter-joint coordination during the timed "Up and Go" (TUG) test of functional movement in an attempt to provide more information regarding the underlying coordination patterns of older adults that might contribute to an increased fall risk. Motion data from fourteen older and fifteen young adults performing the TUG test were analyzed using the Relative Coordination Metric (RCM). Significant differences in TUG task completion time were found between young and old populations. While TUG task completion time has been shown to correlate strongly with fall risk, no significant differences in RCM values were found when averaging across the gait phases. While older adults might require more time to complete a TUG task, the basic inter-joint coordination patterns utilized during gait seems to be preserved, suggesting a potential mechanism by which the brain is able to compensate for physiological changes due to aging.

Thesis Supervisor: Leia Stirling
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Table of Contents

Introduction

As America's aging population continues to grow [1], falls are an immense source of physical, social, and economic hardship among older adults. One in four Americans aged 65 or older falls each year, resulting in more than 2.8 million visits to emergency rooms for fall-related injuries annually and making falls the leading cause of fatal injury for older adults [2]. Falls not only create a significant financial burden (the total cost of injuries due to falls was $50 billion in 2015 [2]) but can also significantly reduce quality of life. An increasing number of elderly individuals fear falling, as the of loss of independence that results can cause further physical decline and even depression [2].

A variety of factors that contribute to a person's risk of falling have been identified. These include deteriorations in balance [3], gait impairments [3,4], diminished visual acuity [5], and musculoskeletal weakness [6]. It is hypothesized that compromised coordination, defined as a decrease in the ability to properly time the motion of body segments with one another [7], may also be a contributing factor to the high rate of falls in older adults. Coordination plays an important role in balance and mobility [8] and decreases in aging populations [9]. Furthermore, James et al. [11] found that impaired gait and rhythmic interlimb ankle coordination (measured using the Phase Coordination Index (PCI), [10]) are associated with a history of falls in the past year. Thus, coordination is often used by clinicians as a measure to help predict a patient's risk of falling, as well as by therapists to measure progress during rehabilitation programs [12]. However, these assessments are currently evaluated subjectively [12], motivating the need for an objective measure of coordination.

Various metrics have been established in an attempt to measure coordination and aid clinicians in their evaluation of a patient's overall functional mobility in a consistent, quantitative manner. One such measure is the time required to complete a timed-up and go (TUG) test. The task involves the participant rising from a chair, walking three meters, turning around, walking back, and finally sitting back down. TUG performance requires both static and dynamic balance and decreases significantly with mobility impairments. Scores greater than 12 seconds indicate a high risk of falling [13].

Metrics aimed at quantifying coordination using sensors such as motion capture and inertial measurement units (IMUs) show promise in detecting changes in gait due to aging and disease. One such metric is Continuous Relative Phase (CRP). CRP has been applied to cyclic motions such as running [18] as well as for the analysis of pathological gait patterns in experimental studies [14-17]. However, it comes with distinct limitations that prevent its effectiveness in clinical settings. Because CRP relies on two transformations into phase space, previous work has shown that CRP should be used to understand relationships in phase-space only and should not be used to make interpretations regarding the original time-series [19]. The transformations away from the original motion make it difficult to infer the underlying movement patterns and identify *where* in the gait cycle a given deficiency may exist. Such an ability is important for clinicians, as it allows for the development of more targeted and efficient rehabilitative programs for their patients. The Phase Coordination Index (PCI) is another metric designed specifically for the analysis of bilateral coordination during gait tasks [10]. While more intuitive and easier to relate back to the original motion than CRP, as it does not require the double transformations into phase space, PCI is limited in that it can only be used to measure coordination between limbs and not between coupled degree-of-freedom joints. In the clinic, the ability to evaluate inter-joint coordination would be valuable, as a number of physical impairments could result in a given bilateral gait asymmetry. An assessment of inter-joint coordination could reveal insights into specific muscle weaknesses, injured areas, and other deficiencies not detectable by an analysis of bilateral gait coordination alone.

In this study, the Relative Coordination Metric (RCM), a measure previously applied to quantity coordination of non-cyclic upper extremity motion during a reach, grasp, transport, and release task [20], is applied to measure lower extremity inter-joint coordination in healthy young and older adults during the TUG test of functional mobility. RCM addresses the limitations of previous coordination metrics: it is velocity-based, it can be applied to non-cyclic motions, is more intuitive, and can more easily be related back to the original kinematics. RCM is applied here to test the hypothesis that there is a significant difference in hip-knee, hip-ankle, and knee-ankle coordination among healthy young and older adults. The ability of the metric to distinguish such differences may play a critical role in further establishing a means for clinicians to better diagnose and monitor fall risk in aging populations in a consistent and quantitative manner.

Methods

Participants

We studied 15 healthy young (M = 20.73 years, SD = 1.79) and 14 healthy old (M = 68.86 years, SD = 6.61) participants, where a younger subject is defined as an adult between the ages of 18 and 30 and an older subject is an individual 65 years or older. Exclusion criteria included any history of neurological impairments, musculoskeletal abnormalities, vestibular disorders, or uncorrected visual impairments, as well as surgeries performed within the previous six months or physical limitations which would require an assistive device. The MIT Committee on the Use of Humans as Experimental Subjects approved this study and all participants provided written informed consent before participating.

Data collection and processing

Participants were first fit with a full-body marker set consisting of 48 retroreflective markers. Participants were also fit with a set of eight strap-on IMUs, although data from the IMUs were not analyzed in the current study. The positions of the reflective markers were chosen according to a modified Cleveland Clinic lower body marker set (Figure 1). Only data from the TUG tests were used in the present analysis. Participants also completed one 10-meter walking test and three standing balance tests prior to the TUG trials, as well as three additional standing balance tests and one walking test following the TUG trials. Data collected from these trials may be used in future experiments. Participants completed a minimum of 15 TUG test trials during this experiment. Data from the first five training trials were not analyzed to reduce any learning effects associated with repeating the task. In addition, trials during which an adverse event or interruption occurred were repeated until a total of 10 trials following the initial five training trials were recorded. A total of 290 trials were analyzed over both subject populations. Participants began each TUG trial sitting upright on an adjustable stool whose height was set such that the subject's legs formed a 90-degree angle. When cued, the participant stood, walked three meters to a turnaround point, walked back to the stool, and sat, thus ending the trial. A 14-camera motion capture system (Bonita, VICON Inc., USA) recorded marker data at 100 Hz. Marker data were reconstructed and processed in Nexus (v2.8.1, VICON Inc., USA) before being imported into Matlab (v2018a/b, The Mathworks, Inc., USA) and filtered using a zero-lag, sixth order, low-pass Butterworth filter with 30 Hz cut-off frequency. Data were imported into OpenSim 3.0 [21] to perform inverse kinematics to calculate joint angles of the lower extremities using OpenSim's gait 2392 model [22]. This method minimizes error between the assumed placement of markers relative to an ideal biomechanical model (scaled for each subject) and the measured marker position from optical motion capture. Anthropometric measurements derived from the participants' marker data while static were used to scale the generic OpenSim model to each subject. Gait events to include foot strikes and temporal parameters such as the start and end of the trial, standing phase, and sitting phase were determined using marker and joint kinematic data per the movement segmentation methodology outlined in Schot et al. [23].

Derivation of Relative Coordination Metric (RCM)

Using the joint angles for the hip, knee, and ankle, angular velocities were calculated. As the number of rotation axes is different for each joint and the joint angular velocities are projections onto these axes, the total angular velocity about each joint is calculated by taking the L^2-norm about these axes. The RCM modifies the L^2-norm angular velocity in order to appropriately compare joints with varying characteristics and degrees of freedom as follows:

$$\Omega_i(t) = \frac{\sqrt{\sum_{n=1}^{N}(\frac{\omega_{n(t)}}{j_n})^2}}{N * J_T} \qquad (1)$$

where N is the number of joint degrees of freedom, $\omega_n(t)$ is the angular velocity component of joint axis n at time t, j_n is a normalization parameter specific to each joint, and J_T is a normalization parameter for all joint axes. A variety of normalization schemes have been previously explored, and each has distinct effects on the values of j_n and J_T to be used in the equation above [20]. Here, we chose to normalize by joint angular velocity such that j_n is the maximum angular velocity for each joint and $J_T = 1$. The maximum angular velocity for each axis was computed over the course of each TUG trial. The hip was defined to possess three degrees of freedom, the knee with one degree of freedom, and the ankle with two degrees of freedom. From Equation 1, the RCM is defined as

$$\rho_{12}(t) = 2\tan^{-1}(\frac{\Omega_1(t)}{\Omega_2(t)}) - 90° \qquad (2)$$

where $\rho_{12}(t)$ represents the RCM between body segment 1 and body segment 2. The RCM can range from -90° to +90°, where values closer to 0 indicate a higher level of coordination. Positive values of ρ_{12} indicate a motion dominated by body segment 1, while negative values of ρ_{12} indicate a motion dominated by body segment 2. For each subject, the average RCM between proximal joints (hip-knee and knee-ankle) over the course of each TUG test was calculated. Each participant's average TUG test time was also computed.

Results and Discussion

TUG Task Time

Differences in total TUG task completion time were found between older and younger populations ($t(27) = 2.33$, $p = 0.027$, Table 1). Older participants generally required more time to complete the TUG task than did younger participants: the older group completed the task in an average of 12.54 (1.83) seconds while the younger group performed the task in an average of 11.04 (1.51) seconds. These results agree with those of previous studies [24], [25], [26], and support the finding that physiological changes that occur with aging increase the time needed to complete a TUG task. Using a posttest analysis to determine fall risk in older adults, Lusardi et al. [27] determined 12 seconds as the suggested TUG time screening threshold for increased fall risk. This suggests that eight of the 14 older participants for whom data was analyzed could be at risk of falling. However, given the fact that a number of factors could be at play when determining the reason for a longer TUG task time, more information about the participant than TUG time alone is needed to sufficiently support the conclusion that he or she is at a high risk of falling. The RCM is one additional means of informing a decision regarding a particular subject's risk of falling.

RCM Values

Table 2 displays the hip-knee, hip-ankle, and knee-ankle RCM values averaged over all points in the gait cycle, all steps, and all trials for each subject. Neither differences in hip-knee RCM values ($t(27) = -0.55$, $p = 0.58$) nor hip-ankle RCM values ($t(27) = -1.37$, $p = 0.18$) were found to be significant. Additionally, no significant differences were found between young and old knee-ankle RCM values ($t(27) = 0.46$, $p = 0.65$). One potential explanation for the lack of significance could be that these average values were calculated over the course of the entire trial, potentially masking any significant differences occurring during regions of the gait cycle. Future work will entail separating the gait cycle into stance and swing phases to determine whether significant differences exist during individual periods of gait.

Further effort is required to verify the joint angles estimated using OpenSim. Table 3 displays the maximum angular velocities used to normalize the RCM values in addition to the total number of steps for each subject. It can be seen that older subject 16, for example, has an unreasonably high subtalar ankle angular velocity, resulting in RCM values for hip-ankle and knee-ankle that are higher than the other older participants, which also increases the average RCM values. Future work will entail investigating the root of these large deviances in maximum joint angles in an attempt to acquire more accurate RCM values for those subjects displaying anomalous RCM values.

One final potential explanation for the lack of significant differences in RCM values is the possibility that while older subjects tend to take more time to complete the TUG task than do younger subjects, the basic coordination patterns remain unchanged. This hypothesis is supported by Figure 2, which displays the hip-knee, hip-ankle, and knee-ankle RCM values averaged over all steps, all trials, and all participants for the younger and older subject populations in order to view the overall coordination patterns exhibited by both subject populations. The overall coordination pattern exhibited across the gait cycle by the older group closely matches that of the younger group. This interesting finding suggests that despite physiological changes due to aging, the underlying movement coordination pattern may be preserved, indicating a potential mechanism by which the brain is able to compensate for the mobility deficiencies discussed above. Future work will entail an analysis of such gait parameters as stride length and width, as well as range of motion in an attempt to evaluate if other characteristics of gait change while this coordination pattern remains similar between younger and older subject populations. Additionally, data collected from the standing balance and walking tasks will be used to evaluate such physical measures as balance and fatigue, which have been shown to be important metrics used by therapists during rehabilitative programs but are currently evaluated subjectively [12].

Conclusion

Significant differences in TUG task completion time were found between young and old healthy adult populations, consistent with previous such analyses [24-26]. While TUG task completion time has been shown to correlate strongly with fall risk [27], this study applied the Relative Coordination Metric (RCM) to quantify inter-limb coordination in an attempt to provide more information regarding the underlying coordination patterns of older adults that might contribute to an increased fall risk. No significant differences in RCM values were found when averaging across the gait phases, indicating that while older adults might require more time to complete a TUG task, the basic coordination pattern during gait is preserved. Future work will involve an analysis of coordination during individual phases of gait as well as specific gait parameters such as stride length and width. Such an analysis will provide more information to determine the mechanisms that allow inter-limb coordination to be unchanged despite physiological changes due to aging.

Figures

Figure 1

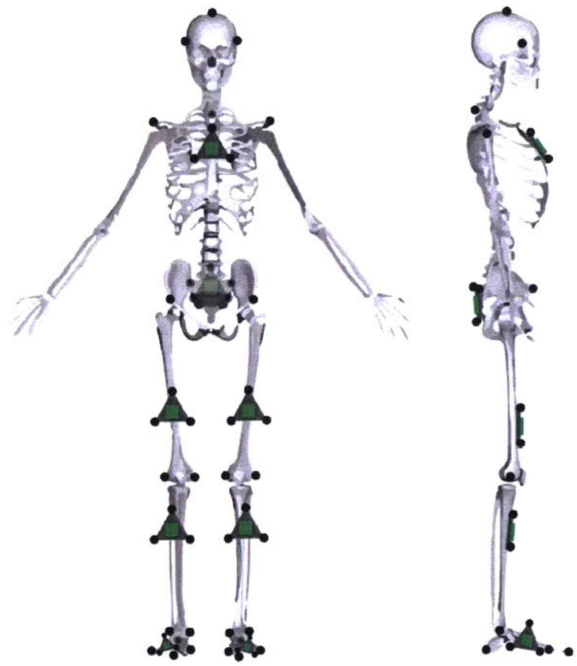

Figure 1. Placement of the reflective markers (black circles) and IMUs (green) on the subject. IMUs on the thigh and shank were not placed precisely, and location varied in the transverse plane.

Figure 2

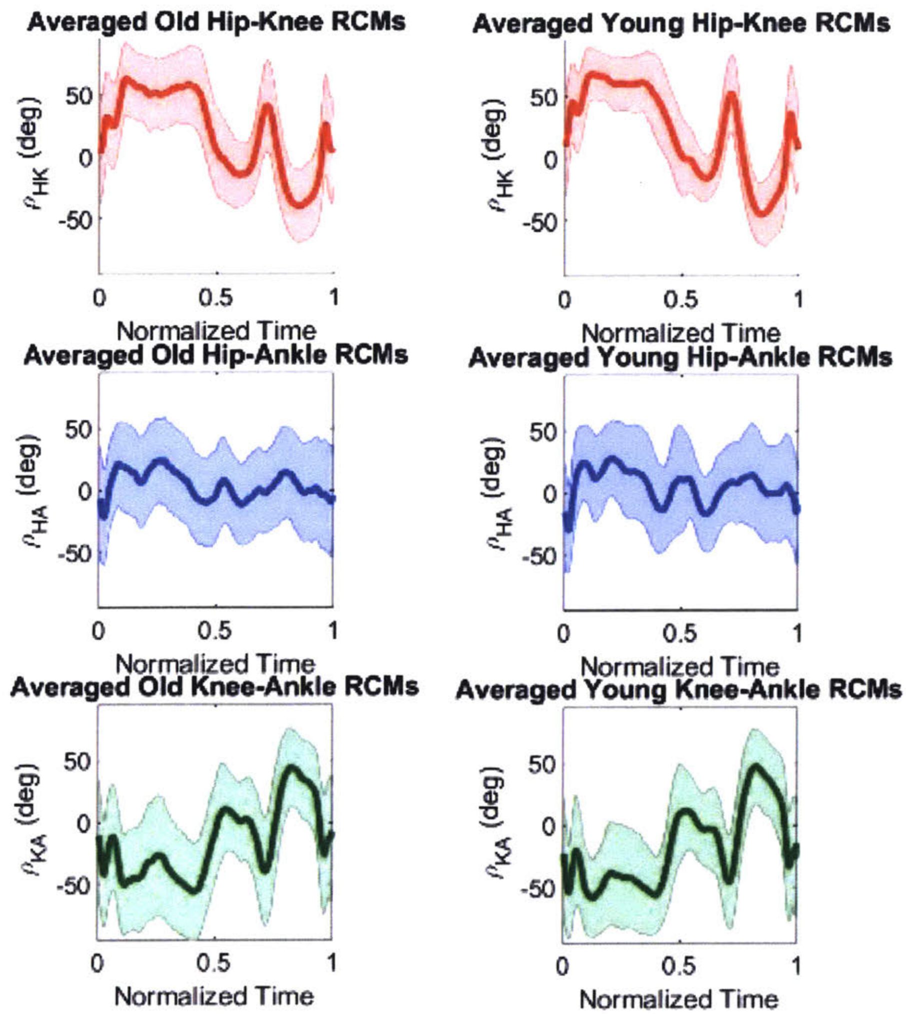

Figure 2. Averaged hip-knee, hip-ankle, and knee-ankle RCM values for older (left) and younger (right) subject populations.

Tables

Table 1

Subject	TUG Time (s)	Subject	TUG Time (s)
O1	13.067	Y1	12.777
O2	10.859	Y2	10.05
O3	11.083	Y3	9.935
O4	10.534	Y4	11.725
O5	14.364	Y5	9.711
O6	15.344	Y6	15.001
O7	17.146	Y7	10.426
O8	12.24	Y8	10.069
O9	12.419	Y9	10.012
O10	11.06	Y10	12.778
O12	11.403	Y11	10.263
O13	11.423	Y12	10.979
O14	12.16667	Y13	10.724
O16	12.431	Y14	12.054
[redacted]	[redacted]	Y16	9.068
Average	**12.53856**	**Average**	**11.03813**
Std. Dev.	**1.825247**	**Std. Dev.**	**1.509189**

Table 1. Total TUG task completion times for all participants. Significant differences were found between older and younger populations, with older subjects generally requiring more time to complete the task than younger subjects.

Table 2

Subject	RCM_HA (deg)	RCM_HK (deg)	RCM_KA (deg)
O1	-2.74634	20.45411	-21.6815
O2	-3.05543	28.91935	-31.3058
O3	-1.22666	21.34598	-23.0345
O4	1.941865	22.94978	-21.0208
O5	7.354917	29.46689	-24.7375
O6	2.243364	26.61306	-24.2435
O7	2.506302	21.79459	-18.1018
O8	-2.27305	11.95964	-13.9453
O9	-9.4337	17.69745	-23.7026
O10	2.995728	18.32598	-16.1097
O12	19.14692	17.18587	0.010721
O13	2.390402	20.86227	-17.2
O14	11.57251	8.807668	2.405171
O16	20.17049	4.879624	14.7414
Average	**3.684809**	**19.37588**	**-15.5661**
Std. Dev.	**8.078627**	**6.8489**	**12.22542**

Subject	RCM_HA (deg)	RCM_HK (deg)	RCM_KA (deg)
Y1	-7.70345	13.89835	-19.7309
Y2	16.32707	25.39022	-13.1432
Y3	11.31721	19.75426	-9.95246
Y4	3.017043	27.0482	-24.5843
Y5	-1.68731	26.29573	-25.8676
Y6	-2.96616	27.79128	-32.7383
Y7	-10.6393	21.44318	-28.6581
Y8	3.595734	27.22301	-25.3926
Y9	1.644314	28.78857	-28.3277
Y10	4.425054	21.1181	-16.8752
Y11	-4.95805	18.95547	-22.2492
Y12	32.27284	13.77296	15.80656
Y13	18.57393	19.88381	-4.13678
Y14	12.74121	22.77518	-16.3047
Y16	10.42888	22.17535	-13.4251
Average	**5.759266**	**22.42091**	**-17.7053**
Std. Dev.	**10.97823**	**4.571711**	**11.73489**

Table 2. Hip-ankle (HA), hip-knee (HK), and knee-ankle (KA) RCM values for all participants averaged over the entire gait cycle, all steps and all TUG task trials. No significant differences were found between older and younger populations.

Table 3

Old Subjects	Hip Flex/Ext (deg/s)	Hip Ab/Add (deg/s)	Hip Rot (deg/s)	Knee (deg/s)	Ankle (deg/s)	Subtalar (deg/s)	Num Steps
1	140.12(25.0)	87.00(12.2)	111.57(24.3)	206.04(49.1)	106.27(29.5)	141.67(31.6)	56
2	136.97(23.2)	93.30(20.0)	89.41(35.3)	245.61(58.6)	119.74(39.3)	130.27(38.0)	54
3	400.63(57.7)	143.44(28.7)	161.01(44.3)	414.61(41.6)	131.79(39.3)	177.24(42.7)	57
4	209.02(37.4)	130.77(28.2)	200.37(70.8)	320.39(44.3)	185.02(31)	215.03(57)	46
5	94.07(19)	52.21(14)	119.40(39)	261.20(57)	146.34(46)	160.50(62)	84
6	215.25(45)	86.08(14)	149.04(73)	312.49(73)	124.95(31)	142.81(167)	64
7	128.68(63)	71.17(30)	117.69(57)	238.36(74)	118.34(268)	213.56(373)	75
8	154.44(32)	108.44(38)	118.18(84)	235.82(84)	197.20(440)	296.82(652)	54
9	177.05(44)	94.26(56)	176.65(52)	277.17(49)	133.63(132)	200.71(243)	49
10	209.83(63)	158.85(112)	379.34(889)	334.48(85)	461.36(1609)	572.45(1628)	45
12	169.79(122)	132.87(124)	437.73(629)	309.55(218)	380.28(634)	569.57(704)	63
13	193.32(52)	81.55(32)	145.85(79)	297.71(72)	239.67(355)	268.26(470)	45
14	179.22(65)	108.20(92)	227.98(215)	236.91(73)	234.82(467)	424.16(672)	53
16	197.64(71)	138.26(94)	282.00(233)	279.84(96)	584.92(1057)	940.94(1461)	57

Young Subjects	Hip Flex/Ext (deg/s)	Hip Ab/Add (deg/s)	Hip Rot (deg/s)	Knee (deg/s)	Ankle (deg/s)	Subtalar (deg/s)	Num Steps
1	186.81(33)	91.15(18)	102.21(25)	232.08(63)	92.42(20)	133.76(29)	52
2	139.88(13)	86.48(22)	100.51(41)	298.83(49)	165.65(43)	254.45(46)	43
3	169.04(37)	81.11(17)	96.59(23)	262.77(77)	236.67(87)	212.14(61)	59
4	142.16(33)	80.63(17)	154.18(37)	237.05(68)	107.51(23)	241.64(86)	51
5	163.67(48)	97.66(25)	203.49(63)	294.26(96)	122.06(37)	281.00(106)	60
6	111.47(9)	39.41(7)	110.75(27)	236.44(22)	93.38(11)	196.43(26)	66
7	187.73(30)	118.61(20)	196.84(47)	270.73(49)	85.64(14)	168.85(41)	70
8	177.38(24)	127.42(14)	241.46(52)	410.51(78)	269.97(423)	354.66(591)	32
9	153.38(14)	99.05(24)	105.88(24)	344.69(58)	141.66(24)	146.96(29)	56
10	129.62(19)	91.54(19)	130.95(33)	270.19(63)	123.38(30)	152.16(36)	59
11	208.45(32)	134.71(30)	216.37(65)	354.83(67)	194.25(67)	245.95(92)	55
12	165.71(29)	108.25(16)	115.40(35)	241.01(50)	503.32(515)	609.98(604)	60
13	126.92(21)	102.21(18)	164.95(57)	307.55(75)	199.88(65)	309.11(91)	50
14	109.47(19)	63.82(17)	117.36(39)	263.41(68)	138.70(46)	169.84(73)	71
16	141.34(22)	109.93(30)	157.96(48)	301.50(71)	135.79(54)	174.38(51)	53

Table 3: Maximum angular velocities averaged over all trials for young and old subject populations and used as the normalization parameters of choice in calculating RCM values in this study.

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