

Proprioception, gait kinematics, and rate of loading during walking: Are they related?

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Abstract

The cyclic nature of walking can lead to repetitive stress and associated complications due to the rate of loading (ROL) experienced by the body at the initial contact of the foot with the ground. An individual's gait kinematics at initial contact have been suggested to give rise to the ROL, and a repetitive, high ROL may lead to several disorders, including osteoarthritis. Additionally, proprioception, the feedback signaling of limb position and movement, may play a role in how the foot strikes the ground and thus, the ROL. Our goal was to explore the relationship between proprioception, gait kinematics and ROL. Thirty-eight women were recruited for gait analysis, and the gait characteristics 50ms prior to and at initial contact were examined. Two proprioception tests, joint angle reproduction and threshold to detect passive motion were used to examine the subject's proprioceptive acuity. Our results indicate that individuals with a larger knee angle (i.e., greater extension) 50ms prior to initial contact (IC) experience a higher ROL during gait and have poorer proprioceptive scores. However, it remains unclear whether poor proprioception causes a high ROL or if a high ROL damages the mechanoreceptors involved in proprioception, but the apparent relationship is significant and warrants further investigation.

Keywords: Heelstrike, Ground Reaction Force, Knee, Women, Osteoarthritis

Introduction

A common activity of daily living is walking, and after the first few years of life, the actions involved in walking are performed with little conscious thought. However, the cyclic nature of walking can impart repetitive stresses on the body, particularly at initial contact (IC), previously referred to as heelstrike^{1,2}. As the leg transitions from the swing phase to the supported stance phase at IC, peak ground reaction forces of 0.5 to 1.25 times body weight can be exerted on the body³.

In the 50ms following IC, a 'shock-wave' traverses the body with the exchange of energy and momentum from the

foot contacting the ground⁴. As the shock-wave is dissipated through the body, it is thought to cause prosthetic joint loosening, stress fractures, tendonitis, headaches, and joint degenerative diseases, such as osteoarthritis⁵. Fortunately, the body has several intrinsic structures to help protect it from IC and to attenuate the subsequent shock-wave. These structures include articular cartilage, menisci, and intervertebral discs and are commonly referred to as shock absorbers³. However, by themselves, the shock absorbers cannot withstand the forces of walking, and with repetitive, high forces, they can experience fatigue failure⁵⁻⁷.

Moreover, it has been theorized that the limb movements prior to or at IC can affect the ground reaction force and the rate of loading (ROL)⁸. Some individuals slow down or stop the foot prior to contact, while others seem to allow the ground to stop the foot^{9,10}. In addition to the downward velocity or acceleration of the foot, the angle at the knee joint has been suggested to be a factor in the ROL^{11,12}. This implies limb positioning can serve as a determinant in an individual's ROL.

Another mechanism the body may use to lower the ROL and reduce the energy of the ensuing shock-wave is through

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Subject Composition and Comparison		
	U.S.A. Median	Overall Subject Composition
Age (years)	20-29	23.5 (2.6)
Height (cm)	162.6	162.9 (4.3)
Weight (kg)	60.5	60.8 (10.0)
BMI (kg/m ²)	22.8	22.7 (2.5)

Table 1. Composition of the thirty-eight subjects compared against the USA median value, reported as mean (SEM) for our values²³.

appropriate limb actions and joint positioning. Proper positioning of the knee prior to IC and eccentric contraction of the thigh muscles at IC help to disperse the load and decrease stress on the joint³. Both of these mechanisms require an intact neuromuscular system for control^{13,12}.

The neuromuscular mechanisms theorized to help prevent damage at IC are the short latency stretch reflex, in which the body reacts after IC to lower the ROL, and anticipatory movements prior to IC to prepare the body. The short latency reflex is induced by the muscle spindle Ia fibers and Golgi Tendon Organ Ib afferents during loading at IC¹³. However, the timing constraint of the stretch reflex poses a problem in controlling the ROL. In walking, the ROL and resulting shock-wave last approximately 50ms, but the short latency stretch reflex activation takes between 34-42ms¹⁴. By the time the body has an opportunity to react to the step via the short latency stretch reflex activity, the shock-wave would have passed the powerful leg muscles that could provide a strong attenuating force^{15,16}.

The second mechanism of anticipatory movements is contingent on the feedback information of proprioception, defined by Sherrington¹⁷ as the body’s awareness to position and movement in space. The feedback information comes from the afferent signals of the mechanoreceptors of the muscle spindles, Golgi Tendon Organs, Pacinian corpuscles, and Ruffini’s endings that respond to limb position and motion¹⁸. During the swing phase, the body receives feedback from the mechanoreceptors concerning the movement, and with the anticipation mechanism, the body would use this information to maintain a controlled movement with feedforward signaling in the subsequent actions¹⁹⁻²¹. Furthermore, it has been reported that if the inertial or initial conditions of the limbs are not considered, the body reacts incorrectly²², and in gait, if the body is not aware of the movements or positions of the limb segments, it may not be able to effectively prepare for the impact and loading at IC.

Therefore, we hypothesize that an individual’s proprioceptive acuity, as determined by the threshold to detect passive motion (TDPM) and joint angle reproduction (JAR) tests, may be related to the knee joint position and leg movements prior to IC, which ultimately may relate to the ROL

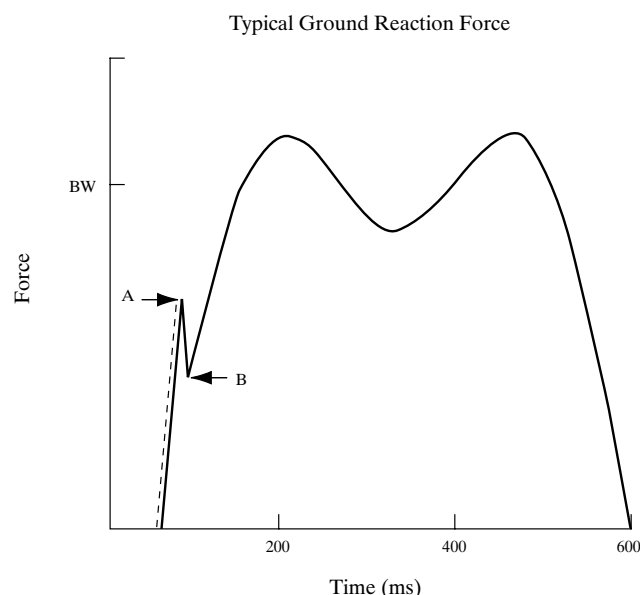


Figure 1. Vertical ground reaction curve demonstrating the heel-strike transient. Point A represents the local maximum force generated within the 50ms after contact. The A/B ratio can be used to classify individuals as heelstrikers or non-heelstrikers. The dashed line represents the portion of the curve used to determine the rate of loading (ROL), and it is normalized by body weight (BW).

experienced. To the authors’ knowledge there is no research explicitly exploring the relationship between an individual’s proprioception with regard to the gait kinematics and ROL. Thus, the purpose of the study was to investigate if gait kinematics during the swing to stance phase transition influence the ROL experienced and to determine if a relationship exists between these actions and proprioception.

Materials and methods

A total of thirty-eight healthy young women, ages 18 to 29 [average (SEM): 23.5 (2.60)], were recruited from a previous study cohort of women, the community and the university campus. All were informed of their rights as study participants and signed informed consents approved by the University’s Institutional Review Board.

Exclusion criteria included the inability to follow instructions, unstable heart conditions, joint replacements in either of the lower extremities, arthritis, diabetes, vestibular deficits or any type of neuromuscular problems that could prevent subjects from meeting the project requirements of a healthy individual.

Subjects were informed they would undergo a series of anthropometric measurements, and proprioception tests, in addition to the gait analysis. Table 1 shows the age and physical characteristics of the subjects, reflecting that they are a representative U.S. sub-population.

Overall Group (N = 38) Characteristics			
Knee angle 50ms before IC (°)	176.1 (0.87)	Relative error JAR average (°)	2.20 (0.53)
Knee angle at IC (°)	177.1 (0.64)	Absolute error JAR average (°)	3.52 (0.35)
Ankle vertical velocity 50ms before IC (m/s)	0.25 (0.017)	Free Speed (m/s)	1.31 (0.031)
Ankle vertical acceleration 50ms before IC (m/s ²)	-1.43 (0.59)	Free Speed ROL (BW/s)	30.2 (3.0)
Ankle vertical acceleration at IC (m/s ²)	-6.12 (0.61)	Free Speed A/B Ratio	1.17 (0.042)
70° TDPM average (°)	2.22 (0.19)	Fixed Speed (m/s)	1.21 (0.026)
Total TDPM average (°)	2.32 (0.21)	Fixed Speed ROL (BW/s)	32.7 (2.6)

Table 2. Average gait characteristics of all the subjects (N=38). All values reported as mean (SEM (SD)). IC = initial contact; JAR = joint angle reproduction; ROL = rate of loading; TDPM = threshold to detect passive motion.

Proprioceptive testing

Two commonly reported proprioceptive measurement tests of the knee were used to examine the subject's proprioception: threshold to detect passive motion (TDPM) for joint kinesthesia and joint angle reproduction (JAR) for joint position sense²⁴.

Our TDPM test was based on the protocol set by Thompson et al.²⁵. The subject's right leg was tested using two starting positions: 45° and 70° of extension from vertical. Twenty TDPM tests were performed at a speed of 0.4°/s, ten at each starting angle, and within each of the ten tests, five were flexion and five were extension movements of the knee joint. Prior to testing the first subject, the order of the flexion and extension movements as well as the starting angle was randomized to prevent learning effects or guessing, and the same order was used for all subjects. In our lab, we had a test-retest repeatability value of 0.87 to 0.94 for the TDPM test²⁵. Averages were computed at each angle and between the flexion and extension results, and a total average was found using all twenty trials.

For the JAR test, we followed work by Baker et al.²⁶. The subject's right leg was tested at target angles of 45° and 70° extension from vertical. The difference between the target and actual angles to the nearest ±0.5 degrees was determined with a Leighton flexometer (Leighton Flexometer, Inc., Spokane, WA, USA). The angles were recorded as absolute error the number of degrees off the target angle, and as relative error using positive degrees off target to represent overshoot and negative degrees to indicate angles and undershoot. Five trials at each target angle were tested for a total of ten trials. Prior to testing, the trial target angles were randomized by interchanging the order of target angles to prevent learning effects, and the same predetermined order was used for all the subjects. In the JAR test, the test-retest reliability was 0.84-0.87 for our laboratory²⁵.

Gait analysis

A six-component, 1000-Hz AMTI force plate (Advanced Mechanical Technology Inc., Newton, MA, USA) was used

to collect the ground reaction force. Subjects were barefoot and instructed to walk normally. To eliminate targeting of the platform, subjects wore special goggles to reduce peripheral vision. Ten successful walking trials were performed per subject, with a successful trial having the entire right foot land on the force plate. The first five of the measured trials were at a "natural pace," similar to a pace the subject would use to cross a street. To eliminate the velocity-dependent effects, the last five trials were performed at a speed of 1.22 ±5% m/s (i.e., between 1.17 and 1.29 m/s), as it is a common speed for most individuals¹. The walking speed was monitored via two telemetric photo cells (Brower Infrared Timing System, Salt Lake City, UT, USA) placed three meters apart adjacent to the walkway, and subjects were informed of their speed after each trial, which allowed them to make speed adjustments on the subsequent trial. Each subject had to perform five trials within the given speed range, and trials in which the subject did not walk within the range were not used for the analysis.

Gait kinematic data was recorded with a 60-fps video camera (Panasonic Model AG-450, Matsushita Electric Industrial Co, Ltd, Okayama, Japan) positioned to the right of the subject. Reflective markers were attached to the subject's right leg at the greater trochanter, center of the lateral knee joint line, lateral malleolus, heel and fifth metatarsal phalangeal joint. The position data of the markers were digitized using the PEAK5 Motion Analysis System (Peak Performance Technologies, Englewood, CO, USA).

A MATLAB (The MathWorks Incorporated, Natick, Massachusetts, USA) program was created to calculate various gait kinematics. The program calculated the following knee and ankle kinematic variables: joint angles, joint velocities, joint accelerations, radial velocities, and radial acceleration at 50ms prior to initial contact (IC) and at IC. We chose to calculate the above variables at 50ms prior to IC because that approximates a typical neuromuscular response time, and it also corresponds to a difference of 3 video frames prior to the IC video frame.

Intragroup Comparisons						
	ExKA		ExVA		ExROL	
	≤-1 S.D.	≥+1 S.D.	≤-1 S.D.	≥+1 S.D.	≤-1 S.D.	≥+1 S.D.
Knee angle 50ms before IC (°)	167.8 (1.8)**##	183.8 (1.3)**##	180.9 (1.7)*	173.5 (1.2)**	172.0 (1.0)*#	179.5 (2.2)*
Knee angle at IC (°)	174.0 (1.0)	177.1 (1.9)	181.3 (0.29)	177.0 (1.7)	175.1 (1.1)*	181.1 (0.75)*
Ankle vertical acceleration at IC (m/s ²)	-3.5 (0.90)	-5.4 (2.0)	-12.3 (1.4)**##	-1.56 (1.4)**##	-5.21 (0.34)	-6.30 (1.2)
70° TDPM Ave (°)	1.55 (0.07)*#	3.05 (0.42)*#	2.58* (0.82)	1.55 (0.11)*#	1.67 (0.13)*#	3.50 (0.18)*#
Total TDPM Ave (°)	1.58 (0.10)*#	3.41 (0.60)*#	2.60 (0.81)	1.68 (0.16)#	1.76 (0.080)*#	3.41 (0.48)*
Relative error JAR Ave (°)	0.34 (0.80)**##	3.61 (1.2)**##	1.97(1.7)	1.18 (1.8)	1.12 (0.8)*#	4.68 (2.3)*#
Absolute error JAR Ave (°)	2.22 (0.22)*#	4.48 (0.68)**##	3.96 (0.80)	3.53 (0.95)	3.31 (1.2)	5.51 (1.0)
ROL (BW/s)	24.0 (3.1)*	47.7 (1.9)*#	38.9 (2.5)*	27.1 (2.4)*	15.1 (1.3)**##	54.5 (2.1)**##
A/B Ratio	1.18 (0.044)*	1.28 (0.056)*	1.29 (0.10)	1.21 (0.032)	1.03 (0.012)*#	1.33 (0.09)*#
Composition (non-heelstrickers / heelstrickers)	4 / 2	0 / 6	2 / 4	4 / 2	6 / 0	1 / 5

* 0.05 ≥ p value > 0.001 between extremes in group; ** p value ≤ 0.001 between extremes in group; # 0.05 ≥ p value > 0.001 between total and extreme group; ## p value ≤ 0.001 between total and extreme group.

Table 3. Gait characteristics and proprioceptive measurement scores of individuals in the extreme groups. All values are reported at free speed and as mean (SEM). ExKA = extreme knee angle group; ExROL = extreme rate of loading group; ExVA = extreme ankle vertical acceleration group; IC = initial contact; JAR = joint angle reproduction; ROL = rate of loading; TDPM = threshold to detect passive motion.

Rate of loading (ROL) and heelstrike classification

The rate of loading (ROL) was calculated from the vertical ground reaction force curve (Figure 1) as the slope from point of IC to the initial peak, point A, which represents the local maximum force generated within the 50ms after contact. The ROL was normalized based on body weight (BW) to allow for comparisons between individuals regardless of weight. The vertical ground reaction forces were also used to classify certain individuals as heelstrickers if they had the ratio of A/B ≥ 1.2, where point B is the subsequent local minimum force after A²⁷. In our study, 16 of the 38 subjects were considered heelstrickers.

Statistical analysis

Initially, we found the mean and standard deviation for the gait kinematic variables for the overall group (N=38). Using the overall group data, we generated a correlation matrix using Sigma Stat 2.0 (SPSS, Chicago, IL, USA), and as the research was exploratory in nature, we used forward stepwise regressions to determine which gait variables most related to ROL and proprioception²⁸. The flow chart in Figure 2 illustrates the analysis method.

Gait kinematic variables identified from the forward stepwise analysis were used to establish extreme groups. To form the extreme groups, the subjects were rank ordered according to the specific parameter of interest (i.e., knee angle 50ms prior to IC, ankle acceleration 50ms prior to IC, or

ROL). For each parameter the top and bottom six individuals in the ranking comprised the extreme groups, for a total of twelve individuals per group. Additionally, a group of individuals with an extreme rate of loading was created in the same manner as the kinematic groups. The locomotor extremes are often used to study animal locomotion because they provide clearer examples of structure-function relationships²⁹. When differences in performance are exaggerated, the relationships, if any, can be made more evident. We also performed intragroup cross-sectional student’s t-tests to compare gait kinematics, proprioception test scores, and ROL between the locomotor extremes. The significance level was p<0.05. If no differences are detected between the extremes, then the odds of proprioception or ROL being related to gait kinematics are small.

Results

Table 2 shows average values of the kinematic variables, proprioception measurement tests, and rate of loading (ROL) for the overall group (N=38). Analysis between the free speed (self-paced) and fixed speed gait characteristics indicated no significant differences in ROL. As a result, further analysis was performed using only the self-paced data, which we felt would be more representative of how the subjects walk on a daily basis.

Knee angle 50ms prior to initial contact (IC) and ankle vertical acceleration 50ms prior to IC were identified in both forward stepwise regression analyses as being significantly

Correlation Co-efficients Between Variables Used				
	Overall (N=38)	ExKA	ExVA	ExROL
ROL – Knee Angle 50ms before IC	0.461*	0.679*	0.545*	0.643*
ROL – Ankle vertical acceleration at IC	-0.391*	-0.371	-0.507*	-0.295
Knee angle 50ms before IC – Total TDPM average	0.313*	0.641*	0.412	0.544*
Knee angle 50ms before IC – 70° TDPM average	0.318*	0.684*	0.510*	0.582*
Knee angle 50ms before IC – Relative error	0.384*	0.581*	0.419	0.441*
JAR average				
Knee angle 50ms before IC – Absolute error	0.398*	0.683*	0.426*	0.439*
JAR average				
ROL – TDPM average	0.218	0.446*	0.238	0.325
ROL – 70° TDPM average	0.329	0.414*	0.259	0.337*
ROL – Relative error JAR average	0.388*	0.557*	0.408	0.414*
ROL – Absolute error JAR average	0.391*	0.540*	0.404	0.474*
A/B Ratio – ROL	0.614*	0.789**	0.624*	0.835**
A/B Ratio – 70° TDPM average	0.592*	0.661*	0.591*	0.812*
A/B Ratio – Absolute error JAR average	0.510*	0.713**	0.679*	0.798**

* 0.05 ≤ p value < 0.001; ** p value ≤ 0.001

Table 4. Correlation co-efficients between gait characteristics and proprioceptive measurement scores in the extreme groups. ExKA= extreme knee angle group; ExROL= extreme rate of loading group; ExVA= extreme ankle vertical acceleration group; IC= initial contact; JAR= joint angle reproduction; ROL= rate of loading; TDPM= threshold to detect passive motion.

correlated to ROL and proprioception. Therefore, the two groups created were extreme knee angle 50ms prior to IC (ExKA) and extreme ankle vertical acceleration 50ms prior to IC (ExVA) for further analysis. Table 3 shows average values for extreme groups, which includes the extreme rate of loading group (ExROL). In the extreme group analysis, we found there were significant differences in proprioception and rate of loading within the kinematic groups ExKA and ExVA groups. In the ExROL group, we found significant differences in proprioception and gait kinematics (Figure 3).

We quantified the relationship between the proprioception scores and the kinematic variables as well as between proprioception and ROL for the overall and extreme groups (Table 4). We found a strong relationship between the knee angle 50ms before IC and ROL in the overall group ($R^2=0.461$, $p<0.05$), and the relationship was also significant in the extreme groups ($R^2=0.545-0.679$, $p<0.05$). When we examined the proprioception scores in relation to the knee angle 50ms before IC, we found that only the 70° TDPM average and JAR absolute error average were significantly related ($R^2=0.318-0.684$, $p<0.05$ for all groups). Additionally, the same proprioception tests were significantly related to ROL in the ExKA and ExROL ($R^2=0.337-0.540$, $p<0.05$). No proprioception scores seemed to be strongly related to the ankle vertical acceleration 50ms prior to IC.

We also noted a strong relationship between ROL and the A/B ratio in the overall group ($R^2=0.614$, $p<0.05$), and with the extreme groups, the correlation increased ($R^2=0.624-$

0.835 , $p<0.05$). We further found the proprioception tests of 70° TDPM average and JAR absolute error average are related to the A/B ratio, the criteria used to examine if an individual is a heelstriker ($R^2=0.510 - 0.812$, $p<0.05$, for overall and extreme groups).

Discussion

Our aim was to investigate if gait kinematics during the swing to stance phase transition affects the rate of loading (ROL) and if a relationship exists between these actions and proprioception. Through the work, we confirmed important factors that affected ROL during gait, as well as determined how proprioception is related to ROL and gait kinematics. First, we found ankle vertical acceleration and knee angle 50ms prior to initial contact (IC) are strongly related to ROL. Second, we noted the proprioception measurement tests of 70° threshold to detect passive motion (TDPM) test average and joint angle reproduction (JAR) test absolute error average were significantly related to knee angle 50ms before IC and ROL, but no proprioception test was strongly related to the ankle vertical acceleration 50ms prior to IC. We noted that the A/B ratio is related to these proprioception tests, and the results from the 70° TDPM and absolute error JAR tests are predictive of ROL. Therefore, the data suggest that ROL is affected by kinematics and limb actions, which in turn are controlled through proprioception.

Only one other study reported actions immediately before

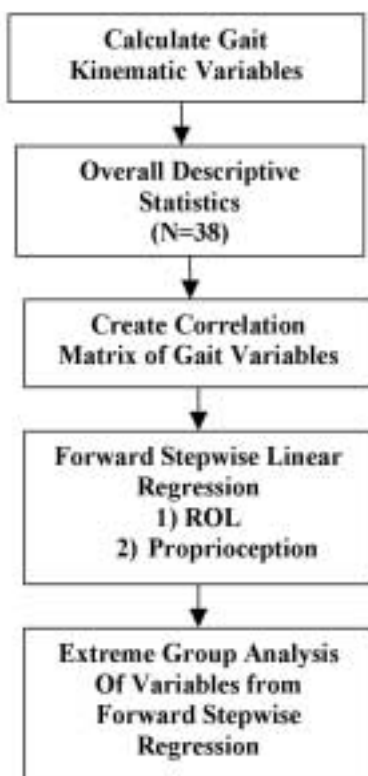


Figure 2. Flow chart of statistical analysis of gait and proprioception parameters.

IC during gait. Radin et al.¹² stated that just prior to impact the control group had an ankle vertical velocity of 0.28 ± 0.03 m/s, comparable to our subjects' velocity of 0.25 ± 0.05 m/s 50ms prior to IC. Additionally, the proprioception results were comparable to earlier studies³⁰⁻³³. As our work is similar to prior published research, we feel confident in our values for the gait kinematics and proprioception measurement scores.

Radin's group¹² reported an average ROL of 47.9 ± 14.4 BW/s for their control group, which did not include subjects with heelstrike transients. Our average ROL is lower (30.2 ± 9.3 BW/s), and it combines both heelstrickers and non-heelstrickers. Their walking speed of 1.37 m/s for the control group was faster than ours (1.31 ± 0.05 m/s), but the small speed difference does not seem to be consistent with the large ROL difference. The ROL dissimilarity between Radin's and our work may result from the method used to obtain the value. They used a linear regression technique to extrapolate their ROL. The sampling rate of the force platform was not reported, but if it were lower than ours of 1000 Hz, data points could have been missed, which could explain the difference between their extrapolated results and our actual results.

Because of the difference, we compared the mean ROL values to work by Munro et al.³³. According to Munro's work, Radin's measured loading rates of 47.9 BW/s correspond to a speed of 1.76 m/s, almost 50% higher than those reported by Radin¹². On the other hand, Munro's study sup-

ports the ROL we found of 30.2 BW/s at the walking speed of 1.31 m/s.

The intragroup cross-section analysis revealed that differences in proprioception do exist between individuals at the extremes of ROL, knee angle, ankle vertical acceleration. We found individuals demonstrating the highest ROL performed significantly poorer on the 70° TDPM test ($3.50 \pm 0.91^\circ$ vs. $1.67 \pm 0.33^\circ$) and absolute error of the JAR test ($5.51 \pm 1.80^\circ$ vs. $2.13 \pm 0.81^\circ$) compared to those with the lowest ROL. In the extreme knee angle group (ExKA), individuals demonstrating the greatest knee extension angle (i.e., having a straighter or hyper extended leg prior to IC) not only had a higher ROL (47.7 ± 10.1 BW/s vs. 24.0 ± 5.0 BW/s), but they also had poorer proprioception compared to the individuals with the smallest knee extensions angles. Individuals with the greatest knee angle prior to IC reported a higher 70° TDPM average score ($3.55 \pm 1.0^\circ$ vs. $1.55 \pm 0.41^\circ$) than their bent knee counterparts in the ExKA group. Therefore, we can conclude that actions just prior to IC are related to the action at IC and can influence the ROL experienced. More importantly, the JAR absolute error and 70° TDPM proprioception measurements may be the ideal tests to predict the individual's characteristic ROL.

The study provides a mechanistic cause for high ROL through the kinematics, as individuals with greater knee extension prior to IC tend to have a higher ROL. Moreover, proprioceptive feedback and control seems to play a role in the kinematics of individuals. Because proprioception influences kinematics, and kinematics affect the ROL, with simple conditional logic, proprioception is a control mechanism for the individual's ROL.

However, Reider et al.³⁵ stated that the individuals with altered kinematics in walking may not necessarily have a loss of proprioception, but that the different movements do not allow the mechanoreceptors to fire as readily. While we cannot state whether the mechanoreceptors are activated differently in subjects with altered movements, such as a greater knee angle before IC, we do know that in the controlled environment of the proprioception tests, there are definite differences in the ability to detect motion and reproduce joint angles.

The proprioceptive tests performed were in a non-weight bearing position, similar to the position where the altered movement occurs, which leads us to believe that observed disparities in proprioception are due to differences in mechanoreceptor activity. It could be that in some individuals, the mechanoreceptors may not be as sensitive to specific movements. Alternatively, it may be that mechanoreceptors have been unknowingly (i.e., no associated pain or acute injury) impaired in individuals with altered movements or high rates of loading, which would lead to the poorer performance in the JAR and TDPM tests. For example, it has been proposed that individuals with excessive joint laxity or microtrauma, a result that can occur from a high ROL at IC¹¹, may have proprioceptive deficits because of the repetitive minute damage to the joint^{36,37}. Furthermore, it has been

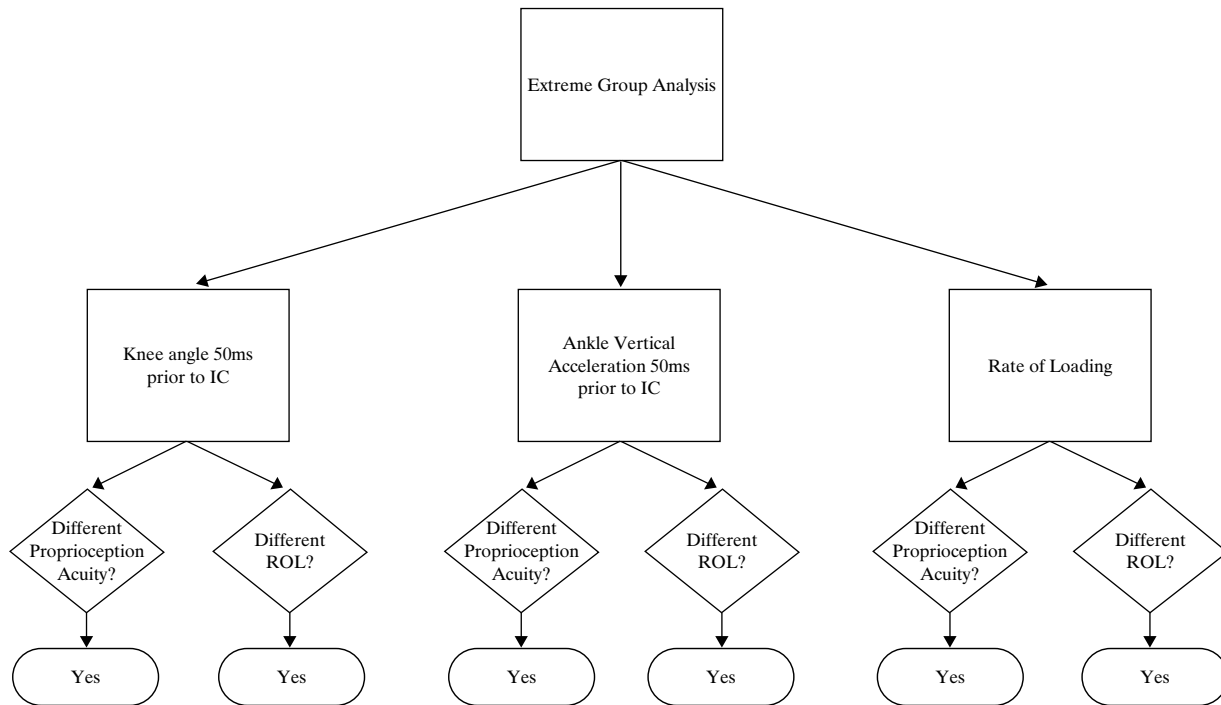


Figure 3. Results of extreme group analysis showing differences between proprioception and rate of loading (ROL) were significant in the extreme kinematic groups. In the extreme ROL group, proprioception scores and kinematics were also significantly different.

suggested that excessive joint laxity may contribute to decreased mechanoreceptor sensitivity because of the looseness of tissues surrounding the joint^{36,37}. We did not examine joint laxity or its relationship to proprioception; however, we did find that individuals with a higher ROL, who would have been the most likely to experience microtrauma from gait, tended to have poorer proprioceptive test scores.

The work is a tentative exploration into some of the complexities of the gait characteristics of the swing to stance transition, and it does not encompass all mechanisms that influence gait. Leg length discrepancies could result in altered gait kinematics, and although we did not observe any gross differences in our subjects, it is possible that small differences could explain some of the variation seen in our kinematic data. EMG records during gait could have explicitly investigated the differences of muscle activation patterns between subjects with high and low rates of loading. Additionally, using two cameras to examine the subject's gait in the coronal plane would provide a three-dimensional view of the subject's gait, which could provide more information on gait kinematics. Eng and Winter³⁸ found that during walking most (84%) of the work involves motions in the sagittal plane and a much smaller amount (11%) involved motions in the frontal plane. Despite these limitations, our data support the concept that individuals demonstrating high rates of loading during gait have poor proprioception acuity.

Conclusion

This work strengthens the concept that proprioceptive acuity is a factor in how individuals walk and the rate of loading (ROL) they experience. Initial correlations of gait variables from the overall group analysis indicated that the knee angle 50ms prior to initial contact (IC) was strongly related to ROL. We also found that proprioceptive measurement scores, from both threshold to detect passive motion (TDPM) and joint angle reproduction (JAR) tests, were related to knee angle 50ms prior to IC. Lastly, we observed that the individuals' proprioceptive test scores were significantly correlated to their ROL.

The extreme group analysis revealed that the 70° TDPM and absolute error of the JAR test were highly correlated with ROL and the A/B ratio, indicating that these two proprioceptive measures may be predictive of gait abnormalities. We conclude that proprioceptive acuity is related to the gait kinematics and rate of loading experienced during walking. However, it is unclear whether poor proprioception causes a high ROL or a high ROL damages the mechanoreceptors, but the correlation is significant and warrants further investigation.

Acknowledgements

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