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Informed Consent Statement

All participants in this study provided written informed consent prior to any data collection or experimental procedures. For participants who were minors at the time of participation, written informed consent was obtained from their parent(s) or legal guardian(s). The research protocol was reviewed and approved by the Nanjing Police University Institutional Review Board for Sports Science Research, ensuring compliance with international ethical guidelines for human subjects research.

The effect of speed and gradient interaction gait patterns on the joint muscles of the lower limbs

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Declaration of conflicting interest

The authors declared no potential conflicts of interest with respect to the research, author-ship and publication of this article.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Conceptualization, D.Z. and F.Z.; Data curation, Y.Z. and F.Z.; Formal analysis, D.Z. and Y.Z.; Funding acquisition, F.Z.; Investigation, D.Z. and Y.Z.; Methodology, D.Z., Y.Z. and F.Z.; Project administration, F.Z.; Resources, F.Z.; Software, D.Z. and Y.Z.; Supervision, F.Z.; Validation, Y.Z. and F.Z.; Visualization, Y.Z.; Roles/Writing - original draft, D.Z.; Writing - review & editing, Y.Z. and F.Z.

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Abstract

To study the effects of fast walking and jogging on lower limb joint muscles at different gradients. 40 healthy young males participated in a 2-phase experiment. Phase 1 assessed "walk→run" and "run→walk" transition speeds (PTS) at various gradients. Phase 2 compared kinematic parameters (sEMG, COM, ROM) between walking and running at 3 speeds (75% PTS, 100% PTS, 125% PTS) and 3 gradients (10% downhill, flat, 10% uphill). ANOVA was used for statistical analysis. PTS varied by gradient (downhill: 7.19 KPH, flat: 7.24 KPH, uphill: 6.63 KPH). Gradient and speed significantly affected gait, especially fast walking. Muscle activity was greater uphill, with shorter step length and frequency. Running had greater COM vertical displacement than walking, smallest on flat ground and decreasing with speed. Ankle and hip ROM were larger uphill, knee ROM larger downhill. Muscle activation increased during fast walking, especially uphill and at speeds >PTS, sometimes exceeding jogging levels. Replacing jogging with 125% PTS brisk walking and incorporating gradient changes can enhance exercise intensity, increase activity and cardiorespiratory endurance, and reduce impact on lower limb joints, lowering injury risk.

Keywords: traveling speed; gradient change; gait pattern; muscle activation; joint angle

Introduction

Rapid changes in lifestyles have led to a sudden decrease in physical activity, which can lead to diabetes mellitus, hypertension, and cardiovascular diseases(Li et al., 2018). The most direct way to change this unhealthy phenomenon is to exercise. For the majority of the general public, most people choose to walk or run for exercise near their homes(Fang et al., 2019). The change of incline (outdoors or in a gym) is an unavoidable environmental factor for exercisers and can improve aerobic capacity, lower body strength, and psychological tolerance(Wang et al., 2014). Physiologically, going uphill increases the activation of the gluteus maximus, vastus lateralis, rectus femoris, gastrocnemius, and soleus muscles in the lower extremities compared to the flat surface, and produces higher oxygen consumption, higher heart rate, and higher blood lactate, thereby increasing workout efficiency(Neves et al., 2014; Padulo et al., 2012). However, it has also been

suggested that downhill workouts increase oxygen consumption, heart rate, and saturation. Although walking or running with an incline can improve exercise performance, it can also change gait(Chen et al., 2007). What are the effects of this change on the human body? How does this change affect the body's center of mass, plantar impact, joint changes, muscle activation, and other elements related to physical activity and injury? In general, individuals walk at lower speeds and run at higher speeds, i.e., there is a marked transition in gait as speed changes(Biewener et al., 2004). Preferred transition speed (PTS) is generally defined as the average of walk-to-run (WTR) and run-to-walk (RTW) transition speeds(Raynor et al., 2002). The physiological view or the muscle activity literature suggests that the exercise benefits of walking are greater than those of running when the travel speed is greater than the PTS. At the same time, slope interventions also considerably impact muscle activity and physical activity levels(Hreljac et al., 2008). Therefore, is it worth discussing the exercise benefits of walking versus jogging when combining the concepts of varying gradient and PTS? Most of the previous studies on gradient variations have compared the differences of a single gait form at different gradients, and fewer have included both walking and running gaits in their analyses and the literature on the differences between brisk walking and jogging at different gradients using the PTS as a demarcation point is also lacking(Luo, J., & Zhang, 2013). Although prior studies showed brisk walking is more active than jogging, the trend at different gradients and associated biomechanical differences are unclear. Additionally, PTS varies due to individual leg length and limb differences, impacting experimental results. Thus, this study uses subjects' PTS to explore the effects of varying gradients on lower limb joint muscles during brisk walking and jogging, offering a scientific basis for exercise mode selection and adjustment.

Methods

Participants

Forty healthy young men were the subjects, with an average age (22.17 ± 2.06) years., an average height (173.12 ± 2.72) cm, and an average weight (63.58 ± 2.87) kg. They had no cardiovascular disease, chronic pneumonia, arthritis, or other diseases, and no lower limb muscle or bone injuries within six months.

This study was approved by the Nanjing Police University Institutional Review Board for Sports Science Research. The study was conducted in accordance with the ethical standards as laid

down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Informed consent was obtained from all participants involved in this study. For participants under the age of 18, written informed consent was additionally obtained from their legal guardians.

Subjects were not allowed to participate in any intense exercise or consume beverages containing caffeine, creatine, branched-chain amino acids, and alcohol for 24 hours before the experiment, and they were required to sleep for at least 6 hours. Subjects drank plenty of water before the experiment, and they stopped eating for two hours before the official test to avoid affecting the metabolism of energy substances. The subjects should drink sufficient water before the experiment and stop eating two hours before the official test to avoid affecting the metabolism of energy substances(Zhang et al., 2020).

Apparatus

Four single-axis force transducers were placed under the ICON Performance treadmill to assess gait and shuffling. The Vicon 3D motion capture system captured and analyzed kinematic data using Vicon Nexus 1.5.2. The BIOPAC MP150 recorder captured EMG and force transducer signals, analyzed with Acqknowledge 3.9.1. A wooden crate, at 10% of the treadmill's uphill incline, created a downhill scenario, calibrated with a Deli DL700600B level. A measuring tape and vernier caliper collected limb segment data.

Design

The PTS defined fast walking and jogging, exploring speed and gradient effects on lower limb joint muscles. The experiment had two phases: pre-experiment (PTS testing at different gradients) and main experiment (walking/running at 75%, 100%, 125% PTS at 10% downhill, flat, 10% uphill). Using ABBA allocation, the study compared lower limb muscle activity, COM, and joint angle changes between gait modes at various gradients.

Procedure

Data collection. Phase 1 (PTS collection at different gradients): Since PTS may be affected by body size, leg length, and cardiorespiratory capacity, the purpose of this phase is to collect the personalized PTS of subjects at different gradients(MacLeod et al., 2014). Initially, subjects walked at 5 KPH, incrementally increasing by 0.2 KPH/15s until they could switch between walking and running comfortably(Hreljac et al., 2007). The same process was then repeated for running-to-walking (RTW), starting at 9 KPH and decreasing by 0.2 KPH/15s. Three successful WTR and RTW

profiles were collected per gradient with 3-minute intervals, with subjects unaware of the treadmill speed. Phase 2 involved walking and running at 75%, 100%, and 125% of PTS across 10% downhill, flat, and 10% uphill gradients, with each 15-second data collection preceded by Vicon system calibration and EMG electrode placement on the rectus femoris, biceps femoris, tibialis anterior, and medial gastrocnemius muscles for maximal EMG recording. The BF, tibial anterior (TA), and medial gastrocnemius (MG) muscles were attached to EMG electrodes and subjected to a maximal voluntary contraction (MVC) test; finally, 39 reflective spheres were attached to the subject's body to replace the human body's limb segments in space (Place et al., 2007). After completing the tasks above, walking and running data were collected at different slopes and speeds. During the experimental process, the reaction force signals generated by the uniaxial force transducer were monitored throughout the whole process in order to avoid dragging or skipping steps; in addition, in order to minimize the effect of fatigue on the electromyographic signals, the subjects rested for 3 min between each data collection.

Data Analysis

Conversion speed (PTS): The three PTS of WTR and RTW were averaged and added together as 100 % PTS, then multiplied by 75 % and 125 % to calculate the three different speeds of the subjects at different gradients, with a total of nine speeds for each subject. EMG signals: The raw EMG was band-pass filtered (10 Hz for low frequency; 500 Hz for high frequency), and then the EMG signals were rectified to the full-wave rectifier at the absolute value, and then the average amplitude EMG values (EMGrms) were calculated as the root-mean-square (RMS). After the above processing, three consecutive gait time points were collected from the Vicon system and applied to the lower limb EMG for activity analysis; each gait was divided into a stance phase (ST) and a swing phase (SW), and the three STs and SWs were averaged; the EMGs of each muscle in the data were divided by the pre-experimental MVC of that muscle and multiplied by a percentage to normalize the results (Zhang et al., 2015). The EMG of each muscle in the data was divided by the pre-experimental MVC of that muscle and normalized by multiplying the percentage. Kinematic parameters: The reflective sphere was used for trajectory repair and data output (the data were interpolated to complete the data in the case of masking), and the three middle stable gaits were taken from each 20 s data for analysis; for gait parameters, the changes of stride length (SL), stride frequency (SF) and stride cycle (SC) were analyzed. In terms of gait parameters, we analyzed the

changes in stride length (SL), stride frequency (SF), and stride cycle (SC) and calculated the stride length using the formula $D=VT$. In contrast, the stride frequency was the inverse of T. Regarding the changes in the center of mass (COM), we subtracted the minimum from the maximum of the COM position in each gait. Then, we took the average COM displacements of the three gaits, which was taken as the change of the COM-vertical (COM-V) for that data, and calculated the medial-medial displacement (COM-MEDIAL-IOCAL) using the same method. COM-medial-lateral, COM-ML); and the lower limb joint movement angles (ROM) were analyzed using the Vicon Nexus output values to analyze the positions of the ankle, knee, and hip joints at the time of Heel Strike (HS) and Toe-off (TO), as well as the positions of the ankle, knee, and hip joints throughout the gait cycle. The differences in joint ROM of the ankle, knee, and hip for walking and running at different gradients and speeds.

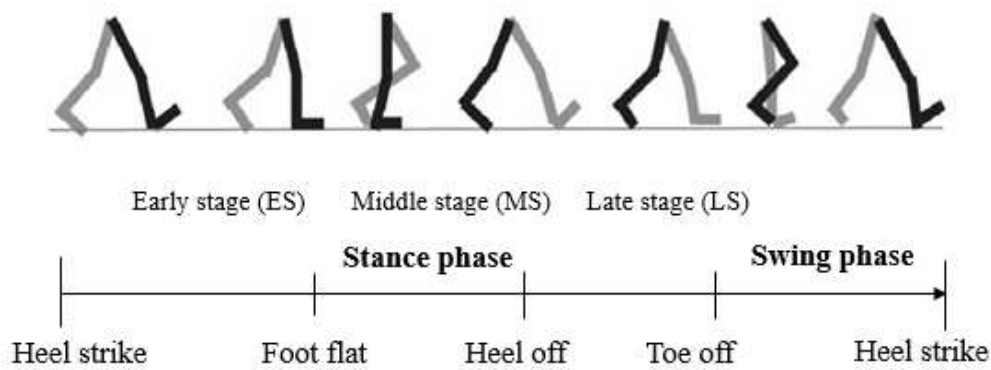


Figure.1 Stride Cycle of this study (right leg as an example)

Statistical analysis

SPSS 19.0 was used for statistical processing, and the results were expressed as mean $\pm$ standard deviation ($\bar{X} \pm SD$). The results were analyzed using a 3-factor repeated measures ANOVA (3 slopes $\times$ 3 speeds $\times$ 2 gait patterns), with a statistical significance level of $p < 0.05$ and a highly significant level of $p < 0.01$.

Results

Different slope PTS

The PTS for downhill, flat, and uphill were 7.19, 7.24, and 6.63 KPH, respectively. Based on these, speeds at 75% and 125% PTS were calculated for each slope, ranging from 6.60-8.00 KPH for downhill, 6.70-7.80 KPH for flat, and 6.30-7.40 KPH for uphill (Table 1). 75% PTS represented

the speed limit for natural running, while 125% PTS was the limit for natural walking.

Table.1 PTS of subjects at different slopes

		Min	Max	$\bar{X} \pm SD$
Downhill	75% PTS	5.00	6.00	5.41±0.27
	100% PTS	6.60	8.00	7.19±0.38
	125% PTS	8.30	10.00	8.99±0.48
Flat	75% PTS	5.10	5.80	5.43±0.24
	100% PTS	6.70	7.80	7.24±0.36
	125% PTS	8.40	9.70	9.05±0.43
Uphill	75% PTS	4.70	5.60	4.98±0.31
	100% PTS	6.30	7.40	6.63±0.39
	125% PTS	7.90	9.30	8.30±0.49

Adjustment of gait parameters

Step length (SL) and step frequency (SF)

SL and SF changes were influenced by gait pattern, slope, and speed (Table 2), and there was an interaction ($p < 0.05$). Against Figure 2, walking SL > running SL at the same speed and slope, and SL increased for the two gait patterns as the travel speed increased; for slope, SL was lowest for walking and running. Compared to Figure 3, when the speed $\leq$ PTS, the SF of running > SF of walking, and when the speed > PTS, there is no significant difference; when walking uphill, the SF is smaller than that of downhill and flat ground, and as the speed increases, the SF of either walking or running increases, and the increase of walking is more apparent than that of running.

Table.2 Effects of different gait, slope, and speed on SL & SF and SC

Source of Variation	Step Length (SL)		Step Frequency (SF)		Stride Cycle (SC)	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Gait Pattern (f1)	26.545	0.000*	53.214	0.000*	59.241	0.000*
Incline (f2)	63.589	0.000*	7.932	0.003*	12.863	0.000*
Speed (f3)	482.365	0.000*	170.38	0.000*	303.185	0.000*
Gait Pattern * Incline (f1*f2)	3.639	0.043*	6.396	0.006*	11.560	0.001*
Gait Pattern * Speed (f1*f3)	23.954	0.000*	98.251	0.000*	218.641	0.000*
Incline * Speed (f2*f3)	40.368	0.000*	6.506	0.000*	10.927	0.000*
Gait Pattern * Incline * Speed	54.773	0.000*	1.216	0.316	2.775	0.074

Note: * $p < 0.05$, the same as below.

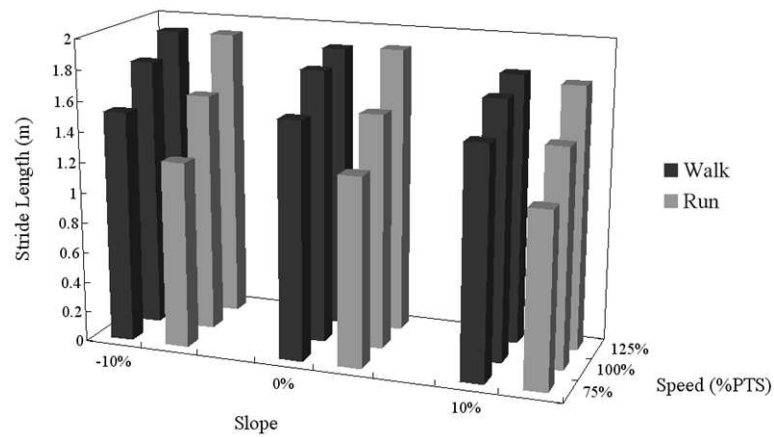


Fig.2 Comparison of SL in different slope, speed and gait

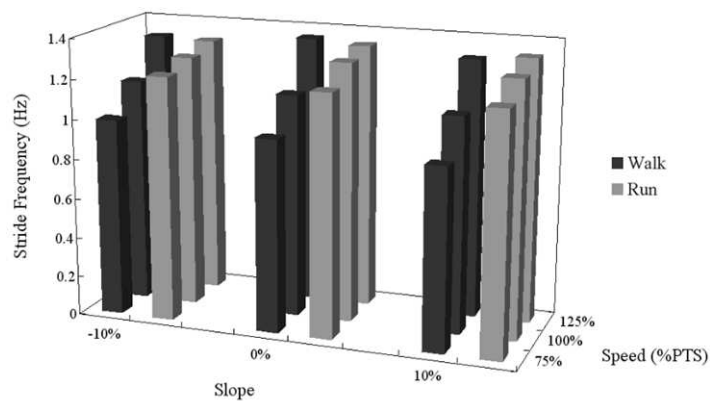


Fig.3 Comparison of SF in different slope, speed and gait

Gait Cycle (SC)

Gait pattern, slope, and speed affected SC (Table 2) and had an interaction effect ($p < 0.05$). Compared with Table 3, at the same slope, the walking and running speeds increased and the SC was shortened; when the walking speed $\leq$ PTS or running speed $<$ PTS, the SC increased with the rise of the slope; when the walking speed $>$ PTS or running speed $\geq$ PTS, the SC was the shortest in the flat ground and the longest in the downhill running.

Table.3 SC in different slope, speed, and gait

Speed	Slope	Gait Cycle (SC)	
		Walk	Run
75%	10%	1.012 $\pm$ 0.06	0.816 $\pm$ 0.02
	0%	1.037 $\pm$ 0.05	0.826 $\pm$ 0.04
	-10%	1.101 $\pm$ 0.06	0.833 $\pm$ 0.02
100%	10%	0.890 $\pm$ 0.07	0.789 $\pm$ 0.02
	0%	0.895 $\pm$ 0.06	0.769 $\pm$ 0.02
	-10%	0.928 $\pm$ 0.08	0.781 $\pm$ 0.02
125%	10%	0.767 $\pm$ 0.07	0.766 $\pm$ 0.02
	0%	0.744 $\pm$ 0.06	0.751 $\pm$ 0.02

10%

0.776±0.08

0.754±0.03

Body center of mass displacement

COM-V and COM-ML were affected by gait pattern, slope, and speed (Table 4) and interacted ($p < 0.05$). Against Table 5, Figures 4 and 6, COM-V change during running > COM-V change during walking, whereas COM-V displacement was the smallest on flat ground among the three slopes, especially when speed > PTS. Comparing Table 5 and Figures 5 and 6, COM-ML displacement was greatest when walking at PTS; up and downhill running had more significant COM-ML displacement when speed $\geq$ PTS, whereas level ground running had the most significant COM-ML displacement when speed < PTS.

Table.4 Effects of different gait, slope and speed on COM

Source of Variation	COM-V		COM-ML	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Gait Pattern (f1)	37.364	0.000*	39.68	0.000*
Incline (f2)	77.692	0.000*	9.41	0.003*
Speed (f3)	8.467	0.006*	0.884	0.427
Gait Pattern* Incline (f1*f2)	128.240	0.000*	6.44	0.006*
Gait Pattern * Speed (f1*f3)	4.620	0.021*	24.22	0.000*
Incline * Speed (f2*f3)	23.851	0.000*	1.94	0.120
Gait Pattern * Incline * Speed	6.725	0.002*	1.63	0.186

Table.5 COM-V & COM-ML in different slope, speed and gait

Speed	Slope	COM-V		COM-ML	
		Walk	Run	Walk	Run
75%	10%	54.23±7.30	82.03±14.75	28.30±9.39	32.04±6.43
	0%	43.30±7.33	73.98±14.26	32.26±6.54	40.27±7.26
	10%	51.06±8.54	74.68±17.93	29.43±4.75	33.93±7.30
100%	-10%	59.56±9.39	89.56±12.39	27.90±5.49	36.67±7.30
	0%	47.06±7.65	83.87±11.77	35.87±7.36	31.33±9.02
	10%	52.28±12.80	85.51±10.43	27.44±5.32	36.25±8.48
125%	-10%	50.04±7.15	92.26±12.69	25.13±4.68	39.16±7.56
	0%	34.98±9.38	90.84±8.31	34.63±6.35	28.17±10.12
	10%	40.79±15.57	90.95±12.94	23.45±4.50	38.76±6.40

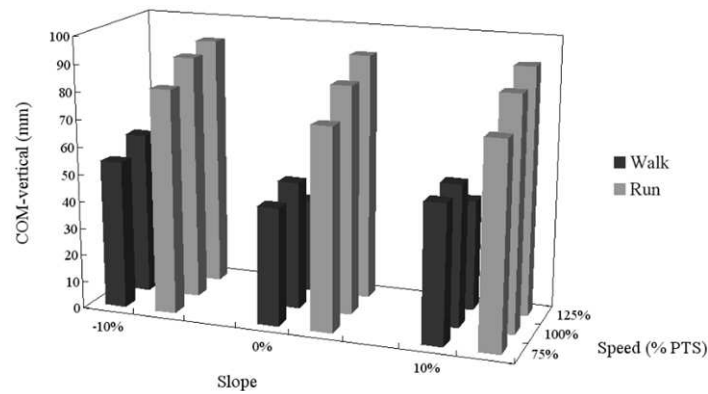


Figure.4 COM-V in different slope, speed and gait

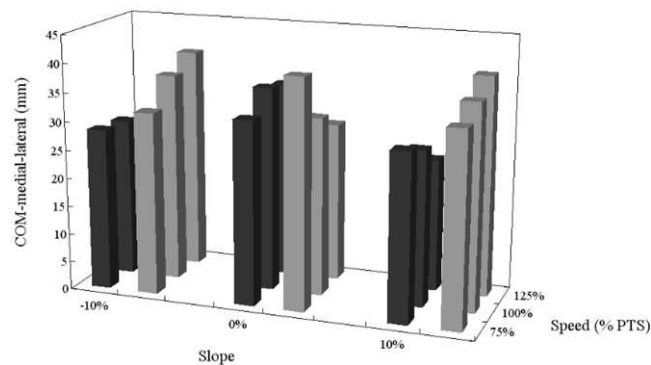


Figure.5 COM-ML in different slope, speed and gait

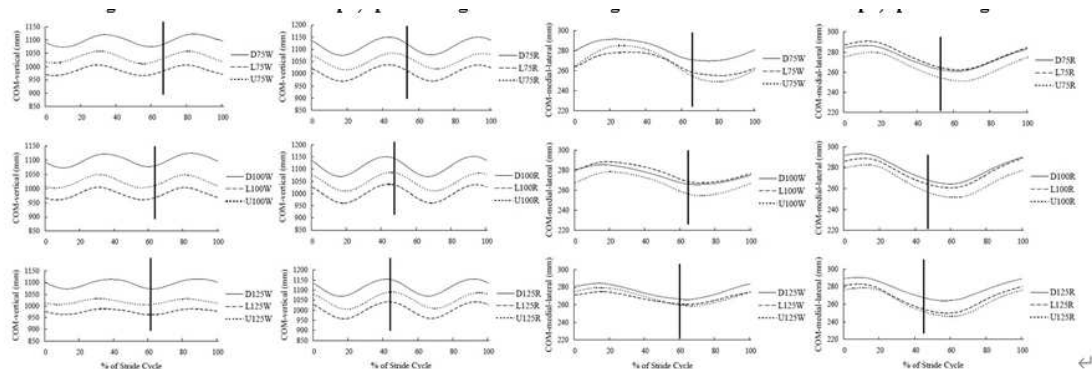


Figure.6 Changes of COM-V & COM-ML displacement

Note: The black line indicates toe off; Columns 1 and 3 represent walking, while columns 2 and 4 represent running.

From top to bottom are three different speeds, and each subplot shows the variations under three different slopes at the same speed. D stands for downhill, L for level, and U for uphill. Same for the following figures.

Lower Limb Joint Angle Changes

Heel-Straight (HS) vs. Toe-Off (TO)

During HS (Table 6), ankle ROM changes were affected by slope and speed, knee ROM was affected by gait pattern and slope, hip ROM was affected by walk-run pattern, slope and speed, and there was an interaction between gait pattern and slope, gait pattern and speed, slope and speed, and gait pattern and slope and speed ($p < 0.05$); comparing with Table 8, it was found that during uphill

(regardless of walk-run), all three joint angles would have greater flexion; the joint angles during walking were affected by speed (the faster the speed, the greater the flexion angle), while the increase in running was not as pronounced as in walking.

Table.6 Effects of different gait, slope, and speed on ROMs when HS & TO

Source of Variation	HS						TO					
	Ankle joint	Knee joint		Hip joint			Ankle joint		Knee joint		Hip joint	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Gait Pattern (f1)	0.005	0.948	29.805	0.000*	99.362	0.000*	21.748	0.001*	18.737	0.001*	21.703	0.001*
Incline (f2)	12.552	0.000*	220.007	0.000*	372.584	0.000*	33.266	0.000*	23.582	0.000*	15.492	0.000*
Speed (f3)	57.550	0.000*	4.273	0.050	100.362	0.000*	44.521	0.000*	95.402	0.000*	28.885	0.000*
Gait Pattern*	5.955	0.022*	14.411	0.000*	43.411	0.000*	2.154	0.158	1.573	0.230	10.497	0.001*
Incline (f1*f2)												
Gait Pattern *	9.606	0.004*	10.712	0.002*	2.849	0.108	2.392	0.115	20.230	.000*	15.071	0.000*
Speed (f1*f3)												
Incline * Speed (f2*f3)	6.276	0.000*	7.672	0.000*	3.937	0.008*	2.588	0.050	0.301	0.875	0.245	0.760
Gait Pattern *	4.191	0.006*	9.702	0.000*	4.228	0.006*	1.510	0.233	0.545	0.657	8.299	0.000*
Incline * Speed												

Tbl.7 ROMs in different slope, speed and gait when HS

Speed	Slope	Ankle joint		Knee joint		Hip joint	
		Walk	Run	Walk	Run	Walk	Run
75%	10%	5.1±5.4	4.3±9.8	3.1±3.4	10.7±4.3	23.6±4.5	19.9±4.0
	0%	3.8±4.2	7.1±6.9	3.0±4.0	15.2±4.4	29.2±5.4	24.7±4.8
	10%	6.3±3.9	11.9±5.9	24.0±6.4	26.3±5.7	46.5±7.1	32.1±4.5
	-10%	9.4±5.8	8.9±9.0	5.3±3.0	9.8±4.5	28.2±5.3	22.8±3.6
100%	0%	8.6±4.4	7.9±7.0	6.7±3.7	14.2±3.6	35.3±5.0	27.1±4.3
	10%	10.2±4.1	11.5±5.2	24.5±7.1	25.6±6.1	51.2±7.1	35.2±4.4
	-10%	13.7±5.7	10.5±6.3	7.6±3.8	9.5±4.6	31.7±4.6	26.5±3.8
125%	0%	13.2±5.2	9.8±5.7	10.5±4.7	13.5±4.6	39.4±6.5	31.1±3.5
	10%	14.1±4.5	13.0±5.0	22.0±5.2	25.3±6.5	50.6±8.1	38.2±4.4

Note: Positive values indicate flexion, negative values indicate extension. The same as below.

At TO (Table 6), the three joints were affected by gait pattern, slope, and speed, and there was an interaction ($p<0.05$). In contrast to Table 8, at the same speed, the ankle joint (both walking and running) had a greater plantarflexion angle on the flat and less on the downhill; the knee joint had a smaller flexion angle with increasing slope; and the hip joint had a reduced straightening angle with increasing slope when walking but a greater straightening angle on the flat than on the other slopes when running. At the same gradient, the ankle and hip joints straightened more with increasing

speed, while the knee joints flexed less.

Table.8 ROMs in different slope, speed, and gait when TO

Speed	Slope	Ankle joint		Knee joint		Hip joint	
		Walk	Run	Walk	Run	Walk	Run
75%	10%	-13.1±4.9	-10.3±7.5	51.9±3.5	47.4±14.5	-7.6±3.7	-2.1±4.9
	0%	-19.1±3.5	-16.9±5.2	44.6±5.1	41.2±13.2	-6.4±3.5	-2.3±3.8
	10%	-17.7±4.7	-15.1±6.1	39.3±5.2	40.7±13.1	-3.5±5.9	2.3±6.4
100%	-10%	-19.0±4.0	-12.3±4.9	46.4±4.6	38.0±13.3	-10.6±4.4	-6.1±4.1
	0%	-23.2±3.2	-19.6±4.3	40.1±5.5	30.3±13.6	-9.5±3.8	-6.6±3.3
	10%	-21.5±3.9	-18.6±5.3	37.2±4.2	30.1±12.9	-4.4±5.5	-3.7±5.0
125%	-10%	-22.6±4.0	-15.6±6.6	41.2±5.0	23.6±7.6	-11.4±5.3	-7.2±5.2
	0%	-24.9±4.7	-20.5±4.7	36.7±6.3	17.0±9.1	-9.0±4.6	-10.5±3.2
	10%	-24.3±5.0	-19.9±5.4	33.6±4.9	15.7±8.1	-3.8±5.5	-8.1±3.6

Maximum and Minimum Joint Angles

Gait pattern, slope, and speed affect the maximum angle of the ankle joint; the maximum angle of the knee joint is affected by gait pattern as well as speed (Table 10), with interactions between gait pattern and slope and between gait pattern and speed ($p < 0.05$); and the maximum angle of the hip joint is affected by gait pattern, slope, and speed, with no interactions only between the gait pattern and speed factors ($p > 0.05$). The maximum angle represented ankle dorsiflexion and knee and hip flexion. When the slope increased (whether walking or running), the maximum flexion angle increased (Table 11). However, when walking, the knee joint had a maximum flexion angle on the downhill slope.

Table.10 Effects of different gait, slope, and speed on Maximum ROM

[illegible]

Tbl.11 Maximum ROM in different slope, speed and gait

Speed	Slope	Ankle joint		Knee joint		Hip joint	
		Walk	Run	Walk	Run	Walk	Run
75%	10%	12.9±4.1	14.9±3.0	71.4±3.7	73.7±5.5	25.8±4.2	23.4±5.5
	0%	12.4±6.6	18.6±5.4	65.4±4.4	70.2±5.3	31.1±4.9	27.7±5.3
	10%	16.6±6.5	26.1±5.4	64.8±4.9	74.5±5.3	47.6±6.8	36.0±4.7
	-10%	12.3±4.2	17.3±4.2	68.8±3.9	76.1±4.4	30.3±5.7	25.6±4.0
100%	0%	11.2±3.4	21.1±3.8	63.0±7.2	74.7±6.9	36.6±5.3	30.0±5.1
	10%	15.6±2.9	27.0±4.1	65.1±5.0	80.1±6.8	52.7±7.4	39.6±4.7
	-10%	16.1±5.4	18.3±3.2	69.7±3.4	84.3±12.3	32.8±4.4	28.9±5.6
125%	0%	15.8±3.9	22.2±3.7	66.2±8.2	85.6±6.7	41.0±6.5	35.2±5.0
	10%	18.2±3.4	28.3±4.1	64.6±5.9	90.2±6.3	52.2±8.1	44.2±5.0

Gait pattern, slope, speed, and the interaction of the three factors affected the minimum angle of the ankle joint ($p<0.05$); the minimum angle of the knee joint was also affected by gait pattern and slope, and the interaction of these factors also had an effect ($p<0.05$); the minimum angle of the hip joint was affected by gait pattern and slope, and there was an interaction between gait pattern and speed, and gait pattern and slope and speed ($p<0.05$). The minimum angle indicated ankle plantarflexion, knee and hip extension angles, and the maximum ankle plantarflexion angle occurred on flat ground (Table 12). In contrast, the knee joint showed micro flexion regardless of the situation.

Table.12 Minimum ROM in different slope, speed and gait

Speed	Slope	Ankle joint		Knee joint		Hip joint	
		Walk	Run	Walk	Run	Walk	Run
75%	10%	-14.9±4.6	-12.2±5.1	1.4±3.1	8.6±4.5	-16.1±3.3	-5.3±3.9
	0%	-21.2±3.5	-17.4±5.2	1.3±3.1	10.5±4.5	-16.5±3.7	-7.7±3.8
	10%	-20.3±4.8	-15.7±6.3	5.6±6.3	16.2±7.0	-13.7±5.2	-3.2±4.9
	-10%	-19.5±3.9	-14.6±3.5	3.2±3.5	7.3±4.6	-16.7±4.6	-7.6±4.3
100%	0%	-23.9±3.2	-20.8±4.1	1.5±2.8	11.6±4.1	-18.3±2.9	-8.6±2.9
	10%	-23.1±3.6	-19.8±5.4	3.5±3.2	13.5±5.2	-13.6±5.2	-6.4±4.6
	-10%	-23.0±4.2	-16.8±5.4	4.9±4.6	6.5±4.9	-15.0±5.5	-8.8±4.5
125%	0%	-25.2±4.7	-23.2±4.0	4.6±3.8	10.7±4.3	-14.3±4.8	-11.5±3.4
	10%	-25.3±4.7	-21.7±5.1	5.0±4.4	11.6±6.0	-10.3±5.6	-9.1±3.7

Trend of joint angle change

At different speeds or gait patterns (Figure. 7), the magnitude of ROM change of the ankle joint was uphill, flat, and downhill in descending order; at different speeds (Figure. 8), the knee joint had the maximum flexion angle for uphill walking, while downhill walking had the maximum dorsiflexion angle; and the hip joint had the maximum dorsiflexion angle for uphill walking and maximum dorsiflexion and extension angles for uphill running at different speeds (Figure. 9).

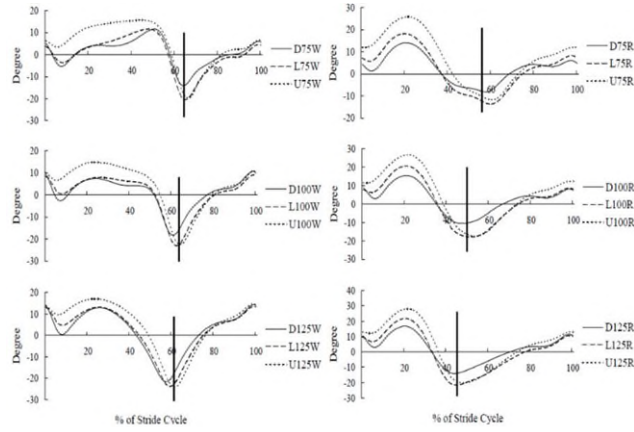


Figure.7 Ankle joint ROM under different speed and slope

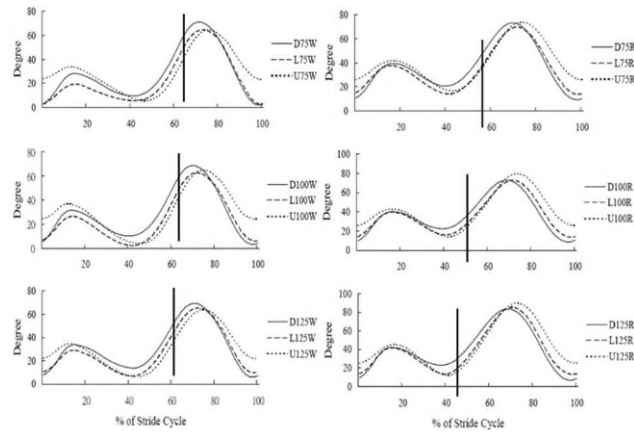


Figure.8 knee joint ROM under different speed and slope

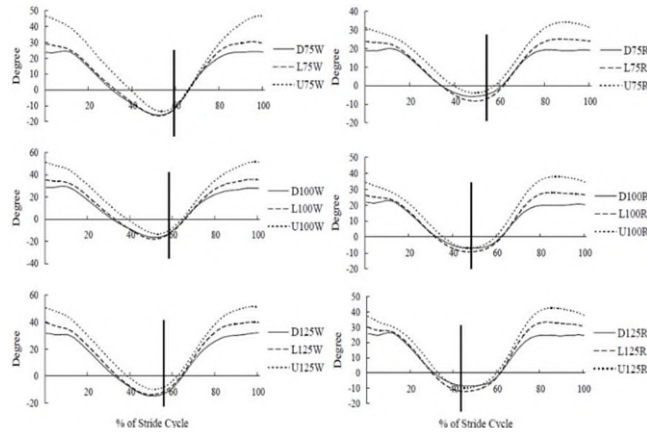


Figure.9 Hip joint ROM under different speed and slope

Lower limb muscle activation

Support period (ST)

The interaction of speed, gait pattern with speed, slope with speed, and gait pattern with slope and speed (Table 13) affected EMG_{RF} ($p < 0.05$); EMG_{BF} , in turn, was affected by the interaction of slope, speed, gait pattern with slope, and slope with speed ($p < 0.05$); EMG_{TA} was affected by gait pattern as well as speed changes, and was also affected by the interaction of gait pattern with slope

MG, and the interaction of gait pattern with velocity ($p < 0.05$); EMG_{MG} was affected by gait pattern, slope, and velocity, while there was no interaction between the factors only between gait pattern and slope ($p < 0.05$). In comparison with Figures 10-13, when walking speed > PTS, walking EMG_{RF} > running EMG_{RF}, except for the small effect of slope change on running EMG_{TA}, all other muscles (both walking and running) increased in activation with increasing slope.

Table.13 mean EMG in different slopes, speeds, and gait under ST

Source of Variation	RF		BF		TA		MG	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Gait Pattern (f1)	2.683	0.130	1.707	0.218	16.287	0.002*	19.786	0.001*
Incline (f2)	2.917	0.075	15.265	0.000*	3.250	0.058	83.839	0.000*
Speed (f3)	113.864	0.000*	41.413	0.000*	48.152	0.000*	202.598	0.000*
Gait Pattern* Incline (f1*f2)	1.444	0.258	6.768	0.005*	8.582	0.002*	0.156	0.857
Gait Pattern * Speed (f1*f3)	20.058	0.001*	0.195	0.730	18.941	0.001*	8.075	0.015*
Incline * Speed (f2*f3)	9.646	0.001*	5.221	0.008*	0.312	0.792	13.004	0.000*
Gait Pattern * Incline * Speed	5.407	0.001*	0.245	0.911	1.183	0.331	3.977	0.008*

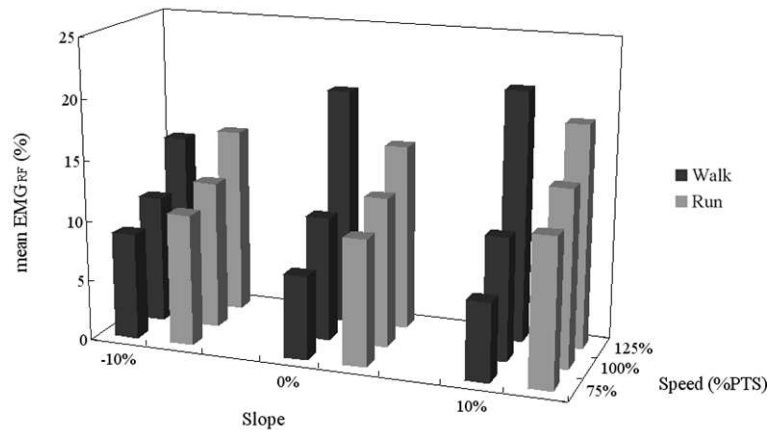


Figure.10 mean EMG_{RF} in ST

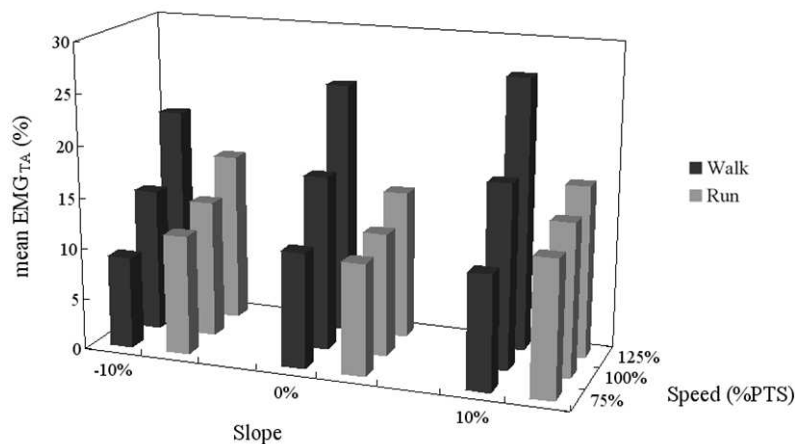


Figure.11 mean EMG_{TA} in ST

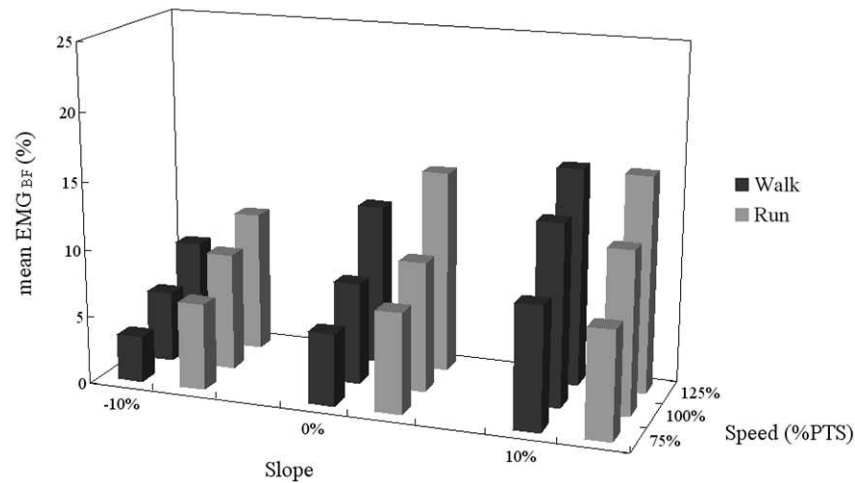


Figure.12 mean EMG_{BF} in ST

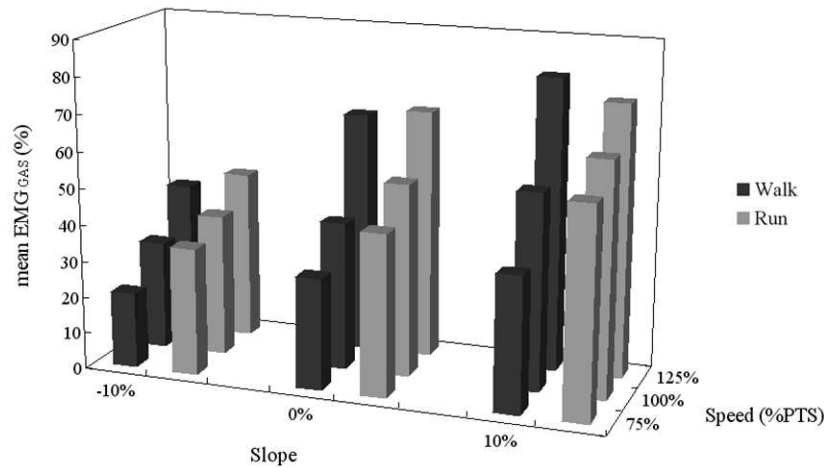


Figure.13 mean EMG_{MG} in ST

Swing phase (SW)

EMG_{RF} was affected by gait pattern and velocity (Table 14), in addition to the interaction between gait pattern and velocity, and velocity and slope ($p < 0.05$); EMG_{BF} was mainly affected by slope and velocity, and there were also interactions between gait pattern and velocity, and velocity and slope ($p < 0.05$); EMG_{TA} was affected by gait pattern, and velocity, as well as the interaction between the two factors ($p < 0.05$); EMG was affected by gait pattern and velocity, and the interaction between the two factors ($p < 0.05$). EMG_{MG} was more influenced by speed and the interaction between gait pattern and speed ($p < 0.05$). In comparison with Figures 14-17, it was found that EMG increased when walking speed increased. In contrast, running was less affected by speed; maximal muscle activation was observed when walking speed $>$ PTS, and EMG was less significantly affected by slope and speed when running.

Table.14 mean EMG in different slopes, speeds, and gait under SW

Source of Variation	RF		BF		TA		MG	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
Gait Pattern (f1)	7.354	0.020*	1.462	0.252	14.889	0.003*	0.004	0.949
Incline (f2)	0.791	0.435	6.141	0.008*	0.070	0.857	0.412	0.668
Speed (f3)	27.208	0.000*	50.339	0.000*	120.609	0.000*	15.914	0.000*
Gait Pattern* Incline (f1*f2)	1.281	0.298	1.085	0.355	1.862	0.179	2.460	0.132
Gait Pattern * Speed (f1*f3)	18.341	0.001*	34.292	0.000*	57.934	0.000*	8.456	0.006*
Incline * Speed (f2*f3)	5.616	0.003*	5.745	0.008*	1.196	0.324	2.015	0.109
Gait Pattern * Incline * Speed	1.936	0.133	0.728	0.516	1.729	0.183	0.227	0.922

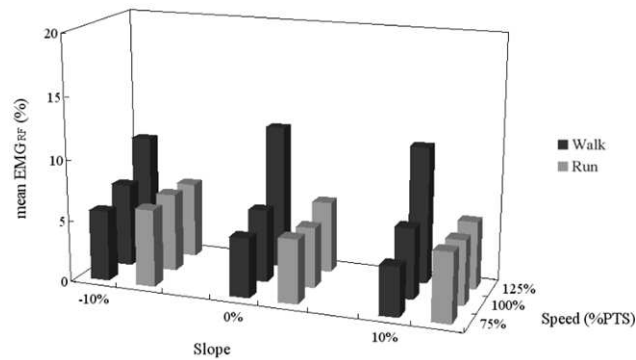


Figure.14 mean EMG_{RF} in SW

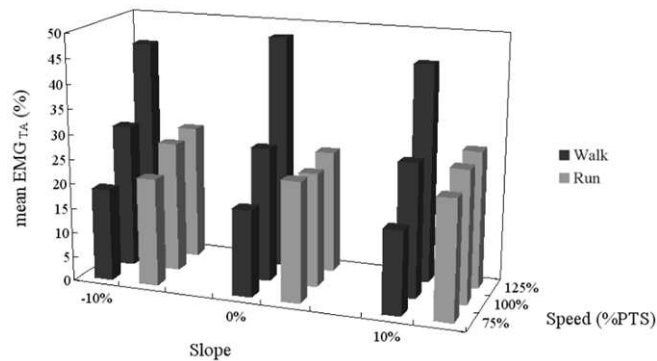


Figure.15 mean EMG_{TA} in SW

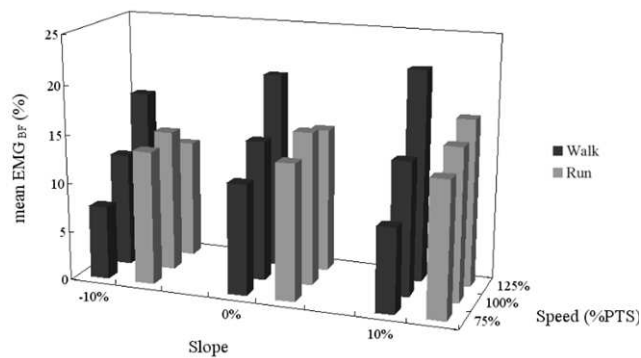


Figure.16 mean EMG_{BF} in SW

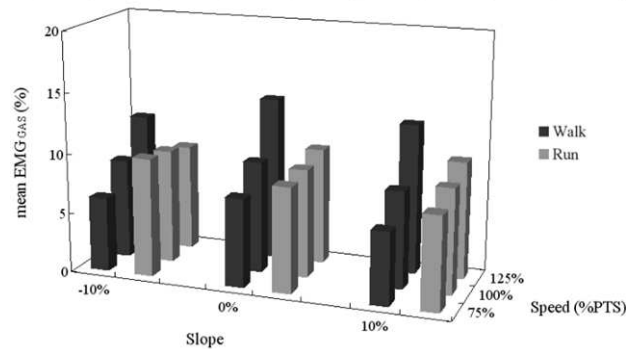


Figure.17 mean EMG_{MG} in SW

Discussion

Individuals walking or running at varying speeds experience significant gait transitions and reciprocal adjustments of SL and SF(Nilsson & Thorstensson, 1987). Segers et al. suggested that spontaneous gait transitions may occur at certain speeds in addition to gait adjustments(Segers et al., 2007). The gait transition was considered a transitional period in the past. However, subsequent studies have suggested that this transition should be a clear point of transition(Raynor et al., 2002; Terblanche et al., 2003), and Li and Hamill have argued that gait transitions are, in fact, a continuous process(Li & Hamill, 2002). Recent literature also suggests that there is more than one point in either WTR or RTW transitions and that the current step in a transition gait cannot be categorized as a walk or a run but rather as a moment(Segers et al., 2013).

Although many studies consider PTS as the mean value of transition speeds for both WTR and RTW, there is a difference of -0.12 to 0.41 m/s between the two, with RTW usually having a larger value than WTR_{PTS}(Getchell & Whittall, 2004). The possible reason for this is the incremental and continuous difference in the measurement methods. The incremental method (used in this experiment) means that the speed increases or decreases for a certain period so that the subject can feel whether it is a transition point (there is no gait transition in the experiment). The PTS error values of WTR and RTW are about 0.02 m/s. In contrast, the continuous method increases the speed steadily (the process can be seen as a real gait transition). However, it is not easy to determine whether it is a transition because of the difference in the nerve. The average error is about 0.13 m/s(13). Since PTS varies from person to person due to the difference in leg length and lower limb length, and the degree of this effect is as high as 30 %(Hreljac, 1993), this experiment is based on the individual PTS of the subjects. The results of this experiment showed that the mean value of

PTS at different slopes was 7.24 KPH on flat ground(Hreljac, 1993). The range for all subjects was 6.70-7.80 KPH, similar to the study of Hreljac et al., who concluded that the spontaneous PTS for the general population to switch from walking to running was about two m/s. However, it was also pointed out that the spontaneous PTS of 4 m/s for the general population was about two m/s for the general population. However, some scholars have pointed out that humans can still walk at a speed of 4 m/s but tend to run at speeds greater than 2.2 m/s, which saves the body's energy expenditure(Kung et al., 2018). Although the physiological energy expenditure of walking at a low speed (1 m/s) is greater than that of normal walking (1.4 m/s)(Sawyer et al., 2010), the energy expenditure of walking is greater than that of running when the speed is higher than 2 m/s(Lussiana & Gindre, 2016). Regarding oxygen consumption, some studies have taken the natural PTS of WTR as the standard and increased or decreased it by 0.5 KPH. It was found that when the walking speed was less than the natural PTS, the maximum oxygen consumption of running would be greater than that of walking. In comparison, when the walking speed was greater than the natural PTS, the maximum oxygen consumption of walking would be greater than that of running(Kobayashi et al., 2018).

From a muscle activity standpoint, there is a natural progression into a WTR gait pattern as walking speed increases to avoid injury to the ankle dorsiflexion and plantarflexion muscle groups from overuse during the SW phase(Neptune et al., 2001). In addition, as walking speed increases (approaching PTS), the ankle dorsiflexion angle and speed also increase; according to the muscle contraction force-length-velocity principle, walking in this state may lead to injuries of the plantar flexor muscle groups, and this phenomenon can be considered as a key factor in the necessity to change from walking to running when speed approaches PTS(Neptune & Sasaki, 2005). In other words, there is a tendency to change gait patterns when running to save energy expenditure when traveling at speeds greater than PTS. Therefore, this study defines 75 % PTS as the speed at which natural running is impossible and 125 % PTS as the speed at which natural walking is impossible. This experiment's mean downhill PTS was 7.19 KPH (similar to flat ground). In comparison, the uphill was 6.63 KPH (lower than that of flat ground), which may be because a change in grade enhances the intensity of the exercise, leading to a relatively lower PTS. The gait results also showed that the SL and SF increased when the speed gradually increased, regardless of walking or running at the same gradient, while the SL and SF were smaller when going uphill with the change of

gradient (regardless of the speed). In the past, studies of different gradients at the same speed have suggested that SL decreases and SF increases (Snyder & Farley, 2011), but the difference between this experiment and the present one is that the PTS is smaller than the other two gradients when walking uphill, so SL and SF decrease when compared to the other gradients, probably because muscle activation of the lower limbs is greater and heart rate and oxygen consumption increase when walking uphill (Yokozawa et al., 2007).

Since running has a period when the toes of both feet leave the ground, the COM-V change of running in this study is significantly more significant than that of walking, and its displacement tends to increase with the increase of speed, which may produce a more significant impact on the joints of the lower limbs. Some scholars tested different gradient running (0 %, ± 5.2 %, ± 10.5 %, ± 15.8 %) at a speed of 10.8 km/hr and found that the peak vertical impact force increased by 54% at -15.8 % downhill running, 34% at -10.5 % downhill running, and 18% at 5.2 % downhill running (Gottschall & Kram, 2005). In contrast, there was no significant difference between the +15.8 % uphill running and running on level ground, which supported the results of the present study. The results of this study are supported. It has been suggested in the literature that decreasing COM-V displacement can increase physical energy expenditure (Kowalski & Li, 2016). Compared to the results of the present experiment, COM-V displacement decreased as walking speed increased, with COM displacement being the smallest at level ground among the three gradients. Compared with flat ground and uphill running, downhill running has a more significant impact on the lower limb impact force, which may weaken the damping effect or increase the vibration frequency of the lower limb (Gimenez et al., 2014). Accordingly, the human body will change the way of landing, the degree of knee flexion, and the stride frequency and stride length, etc. (aiming to increase the damping effect) as a means of avoiding sports injuries, which may be the reason why COM displacement is minimized on flat ground. However, Zhuang Tao and Sun Po et al. concluded that the COM-V acceleration of the human body in the running mode is more variable (Tao, 2012). The intense muscle activity leads to more significant energy expenditure because there is a height difference between uphill and downhill, so the COM-V displacement on the flat ground is smaller than that on the uphill and downhill, and the forward and downward movement of the downhill walking will also make the heel contact with the ground in a low position and form additional sway, resulting in a more significant COM displacement than that on the uphill. Devita et al. found that

for 17 % uphill and downhill running at a speed of 12 km/hr, the peak impact force was 10 N/kg for uphill running and 25 N/kg for downhill running, indicating an increase in impact force of about 2.5 times for downhill running(DeVita et al., 2008). Some scholars disagreed, suggesting a 24.1 % increase in peak vertical impact for downhill running and no significant decrease for uphill running(Telhan et al., 2010). This discrepancy can be explained by the kinematic characteristics of running at different inclines, as there is greater knee flexion in downhill running to increase mechanical cushioning and attenuate impact forces from the ground, and increased knee flexion in the ST phase can significantly increase COM-V displacement and lower limb deformation(Lussiana et al., 2013). The smaller COM-V displacement during downhill running can also be explained using the spring-mass model(Xie, 2018). Therefore, from the point of view of reducing lower limb impact forces and increasing energy expenditure, the exercise benefits and healthiness of fast walking would be better than jogging at travel speeds greater than the PTS. If the effects of muscle activity and joint angle are not considered, and the COM-V displacement is evaluated purely by the amount of COM-V displacement, a walking speed greater than PTS on flat ground will have the smallest COM-V displacement, i.e., the largest energy expenditure. Combined with the results of this experiment, it is hypothesized that under the fast walking mode, as the speed increases, the physiological metabolic expenditure may increase due to the body's need to maintain a stable equilibrium, even though the COM-V displacement becomes smaller.

During HS, the joint ROM increased as the travel speed increased, a phenomenon attributed to the forefoot landing strategy used to reduce braking forces (designed to achieve a fast forward effect) and generate more ankle plantarflexion movements(Hashish et al., 2016). At the same speed, ankle dorsiflexion decreases on level ground but increases when running uphill. Knee and hip flexion increase with gradient for both walking and running. For the same gradient, ankle and hip angles rise with speed for both activities, while knee angles are more affected during walking. The ROM changes are more significant uphill due to midfoot contact and increased knee and hip flexion angles with gradient. In other words, this midfoot-first landing creates extra elasticity in the ankle, which reduces the impact of the ground on the foot, so there is less injury to the foot and less injury to the ankle and knee joints(Lieberman et al., 2010). In TO, ankle plantarflexion is affected by slope, especially downhill. Its angle is limited by TO's higher position, also impacting knee and hip joints. Downhill, knee flexion and hip extension angles are larger due to body posture. Uphill, the opposite

occurs: knees straighten and hips flex less. As speed increases, ankle plantarflexion rises, knee flexion falls, and hip extension increases, reducing energy expenditure by utilizing ankle muscles for ground reaction forces.

Joint ROM differences: Ankle plantarflexion is greater on level ground, less on downhill slopes at same speed. Knee flexion decreases with gradient. Hip extension decreases with gradient while walking, but is greater on level ground while running. At same gradient, ankle and hip extension angles increase with speed. For joint ROM changes: 1) Ankle dorsiflexion increases uphill, especially at 125% PTS; max plantarflexion on level ground; uphill has largest angle change. Speed increase shortens ST phase, advances SW phase, most evident at 125% PTS due to SF acceleration. 2) Knee max flexion occurs during downhill activities; for walking, at SW start due to body posture; for uphill running, in mid-SW to cope with slope. 3) Hip flexion increases with speed and slope due to resistance, aiming to increase SL. Hip extension is greatest on flat ground as slope limits movement.

During the ST phase, EMG increased with walking or running speed and was less significantly affected by the slope. When traveling at speeds more incredible than PTS, the EMG_{RF} of walking was greater than that of running, with a maximum EMG_{RF} at 125% PTS, especially when running uphill, supporting Swanson et al.'s suggestion that uphill running enhances the activation of lower limb muscles compared to running on flat ground (Swanson & Caldwell, 2000). In the present study, activation levels of the BF were increased by both incline and speed, and EMG_{BF} was significantly greater during uphill walking than running. In contrast, TA activation levels were primarily influenced by speed, with EMG_{TA} also increasing when speed was increased. Since the ankle plantar flexor muscle group plays an important role in the ST, forward, and SW phases, it is an important limiting factor that affects whether the human body walks fast or not, which, combined with the experimental results, confirms that the EMG_{TA} is greater when the speed is faster (Zhu & Huo, 2018). This study also found that EMG_{TA} was greater when walking than running at speeds equal to or greater than PTS. As the walking speed was increased close to PTS, the ankle plantarflexion angle and speed also increased, which (based on the muscle contraction characteristics) may cause injuries to the plantar flexor muscle group and, therefore, can be considered as a cause of gait transition as observed in the results of this study. The activation level of MG increased with speed and grade, and the maximum EMG_{MG} was produced when walking at a speed greater than PTS while walking

uphill (greater than running), which is similar to the result of TA, as T was larger than that of running. This result is similar to that of TA, as TA and MG are the primary muscles controlling ankle movements.

In the SW phase: EMGRF during walking rose with speed, more so than during running, especially at speeds above PTS. Slope and gait pattern had minimal impact on RF. BF activity peaked on flat ground at or below PTS speeds, but EMGBF rose with slope at higher speeds, and was greater in walking than running above PTS. TA EMG patterns mirrored ST phase, with EMGTA increasing with speed and being higher in walking than running at or above PTS. Similarly, EMGMG of walking increased with speed and was greater than running above PTS. It's hypothesized that as speed increases, there's a natural shift to a walk-run pattern to avoid overusing dorsiflexor and plantar flexor muscle groups in the SW phase.

Conclusions

(1) Gradient and speed changes impact gait, especially walking compared to jogging. Muscle activity increases uphill regardless of speed, with shorter step length and frequency than on flat or downhill ground. Vertical COM displacement is greater in running than walking, smallest on flat ground, and decreases with speed. ROM increases in ankles and hips uphill, knees downhill. Hip flexion and ankle plantarflexion angles increase with speed to boost push-off power. Muscle activation rises in fast walking, especially above PTS, sometimes exceeding jogging levels. Speed changes affect running EMG less than uphill fast walking.

(2) The conclusions show high-speed walking offers better physiological and biomechanical benefits than jogging, with less impact on lower limbs. Increasing gradient or incline walking can boost activity and train cardiorespiratory endurance. In gyms, 125% PTS brisk walking with incline changes can intensify training, increasing activity and enhancing treadmill effectiveness.

Informed Consent Statement

All participants in this study provided written informed consent prior to any data collection or experimental procedures. For participants who were minors at the time of participation, written informed consent was obtained from their parent(s) or legal guardian(s). The research protocol was reviewed and approved by the Nanjing Police University Institutional Review Board for Sports Science Research, ensuring compliance with international ethical guidelines for human subjects

research.

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