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膝骨性关节炎患者登梯时下肢肌肉活动和膝关节负荷的分析 *

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摘要 目的: 分析膝骨性关节炎患者(KOA)登梯时下肢肌群肌电活动与关节角冲量与正常人的差异,为康复方案设计提供生物力学参考。**方法:** 采用 Qualisys 三维运动分析系统以及 Delsys 无线表面肌电系统对招募 10 名符合纳排标准的膝骨性关节炎患者和 10 名正常人进行登梯活动的步态检测,采用下肢肌群均方根值、股内外侧肌协同收缩比值、股二头肌和股外侧肌共同活动比值和髋、膝关节在冠状面和矢状面上角冲量对比分析与两组登梯时下肢肌群收缩模式对关节负荷的影响。**结果:** 与正常对照相比,上梯时膝骨性关节炎患者股直肌均方根值 RMS(Root Mean Square)增大(P<0.05),膝骨性关节炎患者股内外侧肌收缩均方根值比值(RMS (Vastus Medialis)VM/(Vastus Lateralis)VL)减小(P<0.05),膝骨性关节炎患者腘绳肌与股外侧肌收缩比值(RMS (Biceps Femoris)BF/VL 增大(P<0.05)。下梯时,膝骨性关节炎患者股直肌均方根值(RMS)增大(P<0.05),臀大肌均方根值(RMS)减小(P<0.05),股内外侧肌收缩均方根比值(RMS VM/VL)减小(P<0.05)。上梯时,膝骨性关节炎患者髋、膝关节冠状面上的关节角冲量大于正常人(P<0.05),膝关节在矢状面上关节角冲量大于正常组(P<0.05),下梯髋、膝关节冠状面、矢状面上的角冲量无统计学差异(P>0.05)。KOA 组 VM/VL、BF/VL 与膝关节在冠状面和矢状面上的角冲量的改变没有直接的相关性(P>0.05)。**结论:** 膝骨性关节炎患者在登梯活动时股直肌的收缩活动增加,股内外侧肌的协同收缩下降,主动肌与拮抗肌的共同收缩增加,膝骨性关节炎患者在面对登梯活动时下肢肌群选择性激活和高激活状态协调一致,促进关节稳定。虽然下肢神经肌肉的收缩模式和膝关节负荷之间没有直接的相关性,可能是对膝关节负荷产生影响的生物力学因素较多,神经肌肉的收缩模式只是部分影响因素,后续将增加其他生物力学因素进一步研究。

关键词: 膝;关节炎;登梯;表面肌电图;协同收缩;角冲量;步态分析

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Analysis of Lower Limb Muscle Activity and Knee Joint Loading for Stair Climbing in Knee Osteoarthritis Patients*

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ABSTRACT Objective: To analyze the differences of EMG activity of lower limb muscle group and joint angle impulse in knee osteoarthritis (KOA) patients and normal people, for rehabilitation programmes designed to provide biomechanics of reference. **Methods:** Using the Qualisys 3D motion analysis system and the Delsys wireless surface electromyography system, gait analysis was performed on 10 KOA patients and 10 normal persons who met the inclusion and exclusion criteria, and the root mean square value (RMS) of the lower limb muscle group, the ratio of the synergistic co-activation of the medial and lateral muscles, the ratio of the common activities of the biceps femoris and the lateral femoral muscle, and the contrast of the hip and knee joints on the frontal and sagittal planes was used to compare and analyze the effect of lower limb muscle co-activation pattern on joint loading. **Results:** Compared to the normal control, during ascending stairs, rectus femoris RMS in KOA (P<0.05), the ratio of VM/VL RMS was decreased in KOA patients (P<0.05), the ratio of BF/VL RMS was increased in KOA patients (P<0.05). During descending stairs, rectus femoris RMS increased in KOA patients (P<0.05), gluteus maximus and the ratio of VM/VL RMS descresed (P<0.05). During ascending stairs, the angular impulse of joint on the

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frontal planes of hip and knee joint in KOA patients is larger than that of normal people, the angular impulse of the knee joint on the sagittal plane was greater than that of the normal group. During descending stairs, there was no statistical difference in the angular impulse on the frontal planes and sagittal planes of hip and knee (P>0.05). There was no direct correlation between VM/VL and BF/VL in KOA group and the change of angular impulse on frontal planes and sagittal planes of knee joint (P>0.05). **Conclusion:** In KOA patients, the co-activation activity of rectus femoris increased, while the muscle co-activation of medial and lateral femoris decreased, while the joint co-activation of agonist and antagonist muscles increased. In KOA patients, both muscle co-activation strategies modulate in unison to promote joint stability. Although there is no direct correlation between the lower limb neuromuscular co-activation mode and knee joint loading, it may be that there are many biomechanical factors influencing knee joint loading. The neuromuscular co-activation mode is only a part of the influencing factors, and other biomechanical factors will be added in the future.

Key words: Knee; Osteoarthritis; Stair climbing; sEMG; Co-activation; Angle impulse; Gait analysis

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前言

膝骨性关节炎(Knee Osteoarthritis，KOA)患者由于结构的改变、疼痛、肌肉无力等因素[1]，可能发生了如关节屈曲减小、关节僵硬等运动模式的改变[2]。同时运动模式和姿态的调整也会改变膝关节负荷[3,4]。与平地行走比较，登梯活动需要更大的关节角度和更高的关节负荷，研究证实 KOA 患者登梯活动时关节压力是平地行走的 6 倍[5]，故 KOA 患者常表现出登梯困难和更明显的关节疼痛。一项系统回顾证实[6]KOA 患者在登梯活动中表现出运动学和动力学的改变，同时有神经肌肉的异常活动。所以 KOA 患者在面对登梯活动时下肢神经肌肉、运动模式和关节负荷之间相互影响。另外一方面，KOA 患者在面对登梯活动时通过增强的膝关节肌肉共收缩增强了关节的稳定性，但这也增加关节负荷，可能加剧退变，已经有证据说明加强的内侧肌群的共同收缩加快了 OA 的进展[7]，因此探究膝关节周围肌群收缩对关节负荷影响的研究可能对延缓疾病发展有意义。但目前对 KOA 患者登梯时的肌电活动的研究较少。

研究显示 KOA 患者在矢状面上表现出膝关节外屈曲力矩(External Knee Flexion Moment, EKFM)的降低和在冠状面上膝关节内收外力矩(External Knee adduction Moment, EKAM)的升高[8]。轻度和中度 KOA 患者不仅存在膝关节结构的改变，同时更表现功能性改变。关节负荷与时间因素相关，膝关节内收角冲量(Knee Adduction Angular Impulse, KAAI)是膝关节内收力矩在时间上的积累总和，相对于 KAM 只能测量一个姿态下关节的负荷，KAAI 可以得到整个步态持续时间内的关节负荷信息，是 OA 研究中的反应膝关节内侧负荷的重要步态参数[9]。因此本研究提出假说，认为 KOA 患者登梯时下肢肌群的肌电活动可能存在共同收缩的情况，膝关节负荷冲量可能也表现异常，两者之间可能存在相关性。因此本研究希望通过三维运动分析探究 KOA 患者登梯活动时下肢肌群的肌电活动、肌群的收缩模式和髋、膝关节在冠状面上的内收角冲量变化，为后续设计康复干预方案，提高肌群的协调性及改善膝关节负荷提供生物力学依据。

1 临床资料

1.1 研究对象

本研究的自愿者招募来自福建中医药大学附近社区，对于自愿者的筛查，符合纳入标准者一共 20 例(伦理批件号 2018KY-006-1)，试验组 10 例 Kellgren/Lawrence(K/L)病情程度分级 2～3 级的 KOA 患者，对照组 10 例正常人，两组患者性别、年龄、体质量指数(Body Mass Index, BMI)比较差异均无统计学意义(P>0.05)，具有可比性。详见表 1。

表 1 一般资料比较($\bar{x}\pm s$)

Table 1 Comparison of general information

Groups	Treatment group	Control group	P
Number	10	10	-
Gender	female	female	-
Age (years)	67.10±4.63	63.00±7.44	0.156
BMI (kg/m^2)	24.75±2.71	26.45±2.75	0.182

1.2 KOA 患者纳入标准

符合 2010 年中华医学会风湿病学分会起草的《骨关节炎诊断及治疗指南》[10]的临床诊断标准：1)近 1 个月大多数时间有膝关节疼痛；2)有骨摩擦音；3)晨僵时间≤ 30 min；4)年龄≥ 38 岁；5)有骨性膨大。满足 1)+2)+3)+4)条或 1)+2)+5)条或 1)+4)+5)条者可诊断膝骨性关节炎；影像学诊断膝关节骨赘形成。双侧病变程度基本相同者；年龄 40～75 岁[11]；Kellgren/Lawrence(K/L) 病情程度分级法[12]标定为 2 或 3 级，无需帮助能自己在平地行走至少 6 米及上下四级台阶；自愿参加，并签署知情同意书者。

1.3 KOA 患者排除标准

各种急性、感染性、传染性疾病，内脏功能不全者；其他神经系统或肌肉骨骼系统的疾病影响步态者，如中风等神经源性关节病变，骨折、类风湿性关节炎等患者；Kellgren/Lawrence

(K/L)分级为 0 级正常；1 级，可疑关节间隙狭窄和可能唇状增生；或 4 级，大骨赘，明显关节间隙狭窄、严重硬化和肯定骨端变形者；单侧 KOA 患者或双侧病变程度相差超过 1 级的患者；严重认知障碍[蒙特利尔认知评测(MoCA<18 分)][13]者；其他原因不能配合评估、治疗及检测者。

1.4 正常人纳入标准

年龄 40～75 岁；半年以上无膝关节疼痛、手术史、外伤史的受试者[14]；能自然行走，各关节活动正常；自愿参加本次测试并签署知情同意书者。

1.5 正常人排除标准

存在可能引起步态异常的全身骨骼肌肉疾病或功能障碍者；严重的心脑血管疾病及心理和精神异常者；孕期、哺乳期妇女；身体结构存在明显异常者(如 X 型腿、O 型腿、足弓异常等)。

1.6 方法

1.6.1 动力学数据采集 根据 CAST 下肢模型[15]说明在受试者身上放置好荧光标记物(marker，直径 10 mm)，通过三维运动分析系统(Qualysis Motion Capture Systems，瑞典)，该系统的采样频率为 100 Hz，数据收集后先通过低通滤波(6 Hz)进行处理，去除不需要的数据频率。试验开始前先让患者熟悉走道后才开始记录数据，其目的是为了获得更加准确的数据。要求受试者以自觉舒适的步行速度在平地行走大约 4 m 的距离，然后在三级定制台阶(美国 AMTI stairs，台阶高度为 177.8 mm，深度 267 mm)上进行上下梯试验，台阶顶部有足够的平台空间让受试者可以在上梯后下梯前转身，每侧腿需上下两级台阶。采集登梯步态数据，通过软件 Visual 3D(C-Motion，美国)计算动力学参数与冠状面和矢状面上的关节角冲量，根据地面反作用力可以计算膝关节外膝力矩，外膝力矩在一个完整步态周期时间长度上积累的面积即关节角冲量[16]。

1.6.2 sEMG 数据采集 无线表面肌电系统 Delsys (16 个 Trigno 传感器，尺寸 37 mm×26 mm×15 mm, 16-bit 分辨率，4000 Hz 采样率，<5000 us 传感延迟，波士顿，美国)是一个高性能易于使用的设备，每个传感器都有一个嵌入的三轴加速度计，保证传输范围为 40 m 和最少持续 7 小时的可充电电池。肌电传感器分别被置于下肢的胫前肌、腓肠肌内侧头、股外侧肌、股内侧肌、股直肌、股二头肌外侧头、臀大肌、臀中肌的肌纤维走向上的最隆起处，电极放置位置符合对肌肉无创评估的推荐[17]。被测试的肌肉要经过备皮、刮擦和酒精的皮肤清洁。原始肌电信号经过传感器微分放大器，输入阻抗 10000 MΩ，CMRR>80 Db，增益设为 150，带通滤波 20～450 HZ 进行滤波处理，采样频率 2000 HZ。所有的受试者都会被测对应肌肉的最大自主收缩值 MVIC (Maximum Voluntary Isometric Contraction)进行幅值标准化处理，一共 3 次，每次 3 秒，中间间隔 30 秒休息。采用 Delsys EMGworks Analysis 分析软件(版本号 4.3.1.0)进行数据分析，试验中采集双下肢共 16 块肌肉，以优势腿作为对比分析的目标，计算 RMS 值并做标准化处理后的计算，时间窗口 100 ms，计算登梯过程中一个完整步态周期内的下肢肌群的肌电指标。

RMS 计算公式如下：$RMS=\left(\frac{1}{S}\sum_{1}^{S}f^{2}(s)\right)^{1/2}$

S - Window Length (Points)，*f(s)* - Data within the Window，S 表示时间窗口，*f(s)*表示时长下的 RMS 值。

1.6.3 统计学分析 VM(Vastus Medialis)/VL(Vastus Lateralis)、BF(Biceps Femoris)/VL 的比值计算在 Excel 中完成，统计分析采用 SPSS 20.0 统计软件，计量资料对符合正态分布者采用均数± 标准差($\bar{x}\pm s$)进行统计描述，不符合正态分布者采用 " 中位数 M(四分位间距 *P25*，*P75*)" 表示。计数资料采用频数(构成比)进行统计描述。研究结果统计分析使用遵循研究方案分析(PPT 分析)，脱落者不纳入统计分析。计量资料符合正态分布者，组间比较采用两独立样本 t 检验进行统计推断。非正态分布者，组间比较采用两独立样本秩和检验，检验水准 =0.05。相关性分析符合正态的采用 Pearson 相关分析，不符合正态的采用 Spearman 相关分析。

2 结果

上下梯时，试验组股直肌 RMS 大于正常人(P<0.05)，试验组 RMS VM/VL 小于正常人(P<0.05)。下梯时，试验组臀大肌 RMS 小于正常人(P<0.05)。上梯时，试验组 RMS BF/VL 大于正常人(P<0.05)，见表 3、图 2。上梯时，髋、膝关节在冠状面上关节角冲量试验组均大于对照组(P<0.05)，膝关节在矢状面上关节角冲量试验组大于对照组(P<0.05)，下梯时，髋、膝关节在矢状面和冠状面均无统计学差异(P>0.05)，见表 2、图 1。试验组和对照组 VM/VL、BF/VL 与膝关节在冠状面和矢状面上的角冲量的改变没有直接的相关性(P>0.05)，见表 4。

3 讨论

膝关节是步行和爬楼梯时最重要的负重关节之一。步态过程中，膝关节总负荷的 60-80%分布在膝关节内侧间隙，导致膝关节骨性关节炎(OA)的发病率内侧间室高于外侧[18,19]。内侧负荷即 EKAM 增加更明显。虽然 EKAM 是目前 KOA 研究中关注较多的动力学指标。但一些研究提出，KAAI 比 EKAM 更能作为膝关节内侧负荷的敏感指标[20,21]。故本课题研究采用角冲量反映关节负荷的持续影响，结果提示与正常相比，KOA 患者上梯时在冠状面和矢状面上的膝关节角冲量增大，在冠状面上的髋关节角冲量增大，这些改变是 KOA 患者在面对登梯活动时关节负荷增加的表现。这些改变是 KOA 患者面对挑战性的登梯活动时关节负荷增大的直接证据。

KOA 患者通常存在有膝关节周围肌群萎缩、肌力下降和协调性改变的情况。股四头肌无力是 KOA 患者的常见现象，在无膝痛或肌肉萎缩的患者中也有此类表现，提示股四头肌无力可能是膝骨性关节炎进展的一个危险因素[22]。肌力的下降可能伴随内外侧肌群的不协调收缩[23]。膝关节周围神经肌肉控制的改变干扰正常负荷的分布，促进了膝关节疾病的进一步发展[24]。肌肉的收缩力量和肌电信号 RMS 存在线性相关已经得到证明，故 RMS 值可以表示下肢肌肉的收缩力量 [25]。本研究中 KOA 患者在上下梯活动中股直肌的收缩力均较正常对照组增大，虽然股内侧肌的活动无明显变化，但内外侧比值降低，提示 KOA 患者上下梯过程中为应对登梯这一相对平地行走挑战性较大的活动时，伴随膝关节屈曲程度的增加也需要更有力的伸膝活动，一般研究发现的行走中的股四头肌无力更多可能表现

表 2 试验组与对照组在矢状面和冠状面上髋、膝关节角冲量结果比较($\bar{x}\pm s$)

Table 2 The angular impulse of hip and knee joint on sagittal and frontal planes was compared between experimental group and control group

Project	Groups	Angular impulse (frontal planes)		Angular impulse (sagittal planes)	
		Knee ($N\text{-}m\cdot s\cdot kg^{-1}$)	Hip ($N\text{-}m\cdot s\cdot kg^{-1}$)	Knee ($N\text{-}m\cdot s\cdot kg^{-1}$)	Hip ($N\text{-}m\cdot s\cdot kg^{-1}$)
Stair ascent	Treatment group	0.07±0.02	0.12(0.11,0.14)	0.02(0.01,0.04)	0.04±0.02
	Control group	0.05±0.02	0.10±0.03	0.01±0.01	0.05±0.03
	P	0.031*	0.031*	0.037*	0.244
Stair descent	Treatment group	0.56±0.01	0.10±0.04	0.01±0.01	0.04±0.02
	Control group	0.50(0.45,0.55)	0.10±0.31	0.01(0.01,0.01)	0.03±0.03
	P	0.226	0.906	0.11	0.49

Note: Two independent samples t-test was used for those conforming to normal distribution, and non-parametric test was used for those not conforming to normal distribution, (*)show $P<0.05$.

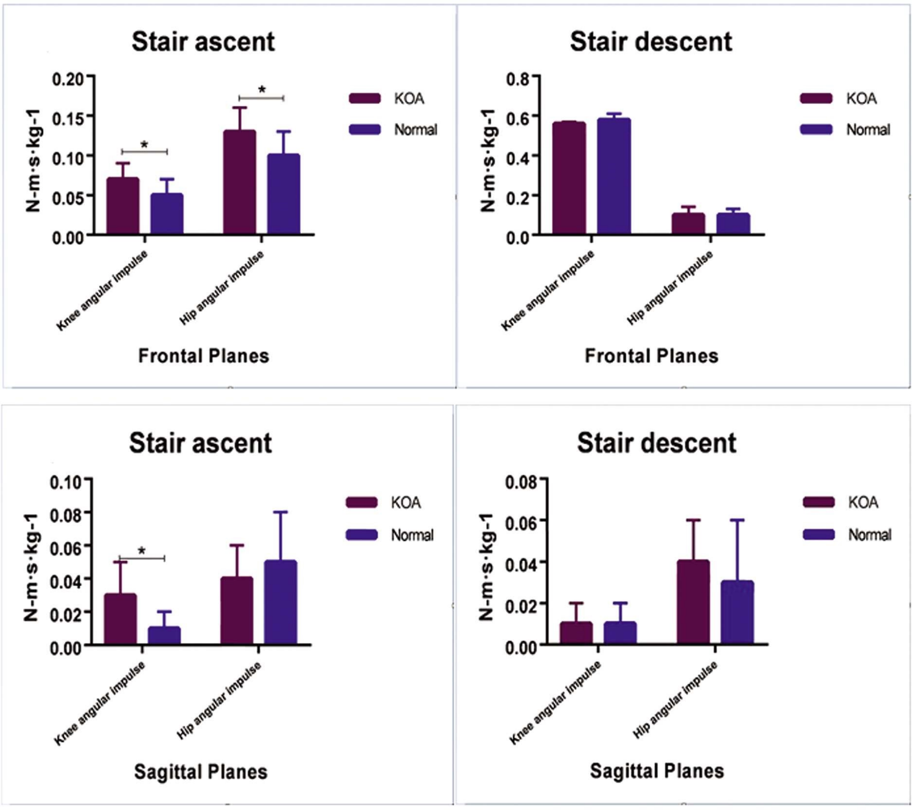

图 1 上梯和下梯时膝关节炎患者和正常人在矢状面和冠状面上髋、膝关节角冲量对比

Fig.1 Comparison of angular impulse of hip and knee joint in sagittal and coronal plane between KOA patients and normal subjects during stair ascent and descent

Note: Data were expressed as $\bar{x}\pm$ SD, n=10. *$P<0.05$.

在内侧肌群相对外侧肌群增强时的不平衡。也有研究表明 KOA 患者面对登梯这种有挑战性的活动时，下肢肌群会有更高的激活状态和收缩模式[26]。股二头肌作为腘绳肌的代表，本研究结果提示上梯时股二头肌与股外侧肌的比值增加，提示主动肌与拮抗肌的共同收缩增加，这可能是 KOA 患者为了维持关节稳定性或内外侧的不平衡，增加腘绳肌的肌肉活动进行代偿[27]。课题前期研究[28]中也显示 KOA 患者在坐站活动中也呈现出腘绳肌激活增加。但下梯时这种共同激活的情况未表现显著差异，可能股直肌的高激活，配合股内侧肌的激活较明显(虽然未表现统计学差异，但有增高趋势)已足以应对下梯时的膝关节稳定性需求。臀大肌的激活在下梯时较正常对照减少，是否也与上述因素有关，同时可能也是 KOA 患者髋策略尚未应用的表现？有研究提示股四头肌无力的 KOA 患者会采用臀肌或比目鱼肌的补偿策略来应对[29]。本研究结果未表现登梯过程中股四头肌的明显不足，股直肌的激活增加是否反而抑制臀大肌的收缩？臀大肌的激活训练是否有助于帮助减少股直肌的过度激活，减少关节负荷？值得后续进一步探讨。

有研究提示 KOA 患者肌肉共激活比率和总和与关节力矩

表 3 试验组与对照组下肢肌肉 RMS 与 RMS VM/VL、RMS BF/VL 结果比较(%, $\bar{x}\pm s$)

Table 3 Comparison of RMS, VM/VL and RMS BF/VL of lower limb muscles between the experimental group and the control group(%, $\bar{x}\pm s$)

Project (RMS%)	Stair ascent			Stair descent		
	Treatment group	Control group	*P*	Treatment group	Control group	*P*
Tibialis anterior	38.48(34.43,53.62)	36.60±9.21	0.096	30.67±13.88	26.32±8.92	0.414
Gastrocnemius medialis	32.24(26.40,36.58)	25.41(21.04,37.45)	0.241	21.44±10.67	18.43(11.53, 21.60)	0.496
Vastus lateralis	49.72±19.34	51.56±8.44	0.788	45.15±14.78	47.76±16.74	0.822
Rectus femoris	37.26±13.40	17.67(11.10, 30.71)	0.019*	37.52±16.03	23.10±10.57	0.029*
Vastus medialis	40.81±11.76	42.77±9.56	0.686	47.68(22.12, 50.17)	36.18(26.77±52.37)	0.880
Lateral biceps femoris	22.27±5.58	25.44±11.89	0.455	16.98±6.36	16.95±6.36	0.993
Gluteus maximus	38.85±9.76	36.70±12.15	0.668	17.67±4.59	29.61±13.71	0.036*
Gluteus medius	26.19±6.98	24.67±9.63	0.666	15.17±6.45	17.70±8.66	0.469
VM/VL	0.655±0.151	0.89±0.265	0.026*	0.69±0.17	0.88±0.20	0.037*
BF/VL	0.60(0.56,0.98)	0.51±0.117	0.028*	0.61±0.32	0.74±0.43	0.466

Note: Two independent samples t-test was used for those conforming to normal distribution, and non-parametric test was used for those not conforming to normal distribution, (*)show P<0.05.

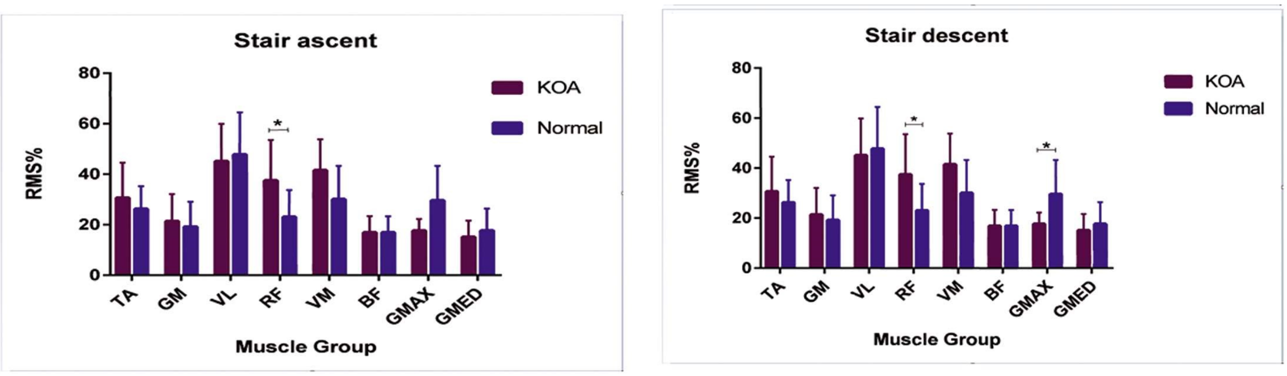

图 2 上梯和下梯膝关节炎患者和正常人下肢肌群 RMS 对比

Fig.2 Comparison of RMS of lower limb muscle groups between KOA patients and normal subjects during stair ascent and descent

Note: Data were expressed as $\bar{x}\pm$ SD, n=10. *P< 0.05.

表 4 KOA 患者 VM/VL、BF/VL 与冠状面和矢状面上关节角冲量的相关性分析(%, $\bar{x}\pm s$)

Table 4 Correlation analysis of VM/VL and BF/VL in KOA patients with joint angular impulse on frontal and sagittal planes(%, $\bar{x}\pm s$)

Groups	Project	VM/VL	Frontal	Sagittal	BF/VL	Frontal	Sagittal
			Knee	Knee		Knee	Knee
KOA	Stair ascent	Co-contraction	0.66±0.15	0.66±0.15	Contraction of antagonism	0.60(0.56,0.98)	0.60(0.56,0.98)
		KAAI	0.06±0.02	0.02(0.01,0.04)	KFAI	0.66±0.02	0.02(0.01,0.04)
		r	-0.25	0.17	r	0.30	0.01
		P	0.48	0.65	*P*	0.39	0.99
KOA	Stair descent	Co-contraction	0.69±0.17	0.69±0.17	Contraction of antagonism	0.61±0.32	0.61±0.32
		KAAI	0.05(0.05,0.06)	0.01±0.01	KFAI	0.05(0.05,0.06)	0.01±0.01
		r	0.25	0.08	r	-0.48	0.12
		P	0.48	0.83	*P*	0.17	0.74

Note: Pearson correlation analysis was used for those conforming to normal, while Spearman correlation analysis was used for those not, (*)show P<0.05.

呈现出强烈的正相关性,肌肉共激活的检测可以解释膝关节相关肌群包括股四头肌、腘绳肌和腓肠肌等对膝关节负荷的贡献情况[30]。但本研究结果未提示肌群收缩与矢状面和冠状面关节角冲量之间的相关性。KOA 患者登梯过程中股内外侧肌协同收缩和腘绳肌与股外侧肌的拮抗收缩与矢状面和冠状面上的角冲量均没有体现出相关性,所以膝关节周围肌群收缩会导致关节负荷增加的假说不成立, 而除了下肢肌群的共同激活外,影响 KOA 患者登梯膝关节负荷的下肢生物力学因素还有很多如躯干的调整[31]、骨盆的运动[32,33]和足部进展角度[3]以及步宽[34]、步速[4]等等,肌群收缩可能只是其中部分影响因素。当然性别和样本量也是本研究的不足,后续将进一步研究。

KOA 患者在面对登梯这种日常活动时膝关节周围神经肌肉的收缩和关节负荷的相对关系值得进一步探讨。

5 结论

KOA 患者在进行登梯活动时, 表现出较高的选择性股直肌高激活、股内外侧肌之间的不协调收缩及上梯时股二头肌与股外侧肌的共同激活增加,在冠状面和矢状面上的关节角冲量均增大, 虽然肌肉收缩与关节角冲量之间没有直接的相关性,但下肢生物力学因素彼此相关,可能神经肌肉的收缩模式通过影响步行速度、骨盆运动等其他生物力学因素间接影响关节负荷。所以在后续的研究中应增加样本量和其他生物力学因素综合研究两者之间的关系,为临床指导提供有力证据。

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