武术跃步冲拳动作的肌肉协同特征及其运动水平差异分析

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摘要：研究目的：武术是中华传统体育文化的重要部分，跃步冲拳作为少年拳的基本套路之一，可以帮助建立符合武术运动规律的动作记忆。跃步冲拳包含多种武术基础动作，需要全身关节和肌群在时间和空间上的协调配合，其质量与神经肌肉控制能力密切相关。研究发现，人体在完成运动任务时中枢神经系统可以通过激活功能模块来协调控制多肌群，这种肌肉协同模式也成为了研究运动技能学习与提升的重要方法，但肌肉协同作用会因运动水平的不同而改变。然而，现有武术研究多数只关注单块肌肉的特征，并且其神经肌肉控制机制也尚不明确。因此，本研究比较专业组和初学者组完成跃步冲拳动作时肌肉协同特征的差异，深入分析其神经肌肉控制机制，不仅为运动技能提升和科学化训练提供理论基础，还可以为运动员和教练员提供动作标准化的量化依据。**研究方法：**本研究共招募 22 名男性大学生，分为专业组（n=11，武术主项学生，身高 181.75±1.35cm，体重 75.75±2.15kg，武术专项训练年限 2.91±0.19 年）和初学者组（n=11，身高 183.25±2.57cm，体重 75.25±3.22kg），近 6 个月均无运动损伤史或手术史。专业组进行系统武术训练至少 2 年，每周训练至少 3 次且技术规范。初学者组未接受系统武术训练但具武术课程学习经历。采用 Vicon 三维动作捕捉系统和 Kistler 三维测力台采集运动学和动力学数据，通过 Delsys 无线表面肌电采集系统同步采集 16 块肌肉（包含双侧下肢、优势侧躯干和上肢肌群）的肌电信号。热身后，受试者按标准起始姿势（右腿单足站立，左膝屈曲 90°，双臂呈武术起手势）执行跃步冲拳，左脚下落后蹬地跃起，右腿前摆落地，左腿前伸，身体右转重心下移转为右仆步。仆步稳定后，转为左弓步完成冲拳。结合动作特点并根据运动学和动力学特征将动作分为 3 个阶段：跃步腾空（Leap-Flight, LF）阶段、落地仆步（Crouch-Landing, CL）阶段、弓步冲拳（Lunge-Punch, LP）阶段。采用截止频率为 10Hz 和 50Hz 的 Butterworth 四阶低通滤波在 Visual 3D 软件中分别对运动学和动力学数据进行平滑处理。对肌电数据进行预处理，采用截止频率为 50Hz 的四阶零相位 IIR 高通 Butterworth 滤波器进行高通滤波，然后采用截止频率为 20Hz 的四阶 Butterworth 滤波器对全波整流后的肌电信号进行低通滤波处理，得到线性包络线。采用经典高斯非负矩阵分解算法对预处理后的肌电信号数据进行处理非负矩阵分解（non-negative matrix factorization, NMF），将 EMG 数据矩阵 E 分解为运动模块（motor modules）

矩阵 W 和运动原语（motor primitives）矩阵 H，并对 E 进行重构得到 E_r。采用决定系数 R^2 评估 NMF 重构质量，使用线性回归模型对 R^2-r（肌肉协同组数）进行拟合，选取拟合后曲线斜率最大的点所对应的肌肉协同组数作为最佳协同组数。并且采用 k-means 算法对每组所有受试者的肌肉协同作用进行聚类。为了比较肌肉协同在不同动作阶段中的激活特征，计算各组运动原语（矩阵 H）的活动中心（centre of activity，CoA）和半峰全宽（Full Width at Half Maximum, FWHM）。采用 SPSS 26.0 进行数据分析，符合正态性检验时使用独立样本 t 检验，不符合正态性检验时使用非参数检验，显著性水平为 0.05。**研究结果：**1）专业组在跃步冲拳的过程中存在 5 组肌肉协同，初学者组仅提取出 4 组肌肉协同。协同元 5 仅出现在专业组，主要在 LP 阶段激活，表现出上肢肌群和臀肌的高度协同。说明专业组可以在更加稳定的骨盆基础上提升冲拳的爆发力和精准性。协同作用的增加不仅反映了中枢神经系统对调节复杂任务的能力，也可能表明形成了更高水平的动作结构和协同策略。2)专业组和初学者组的组合协同占比差异虽无显著差异，但专业组组合协同占比相对更低，这也从一定程度上说明随着运动水平的提升，肌肉协同的结构可能更清晰，减少了肌肉协同的冗余激活。3）在激活时间结构方面，协同元 3（$p<0.01$）和协同元 4（$p<0.05$）中专业组和初学者组的 CoA 均存在显著差异，专业组在时间分布上激活的更早。协同元 3 主要激活于 CL 阶段，该协同元的提前激活可以减少仆步转换弓步的发力时间。协同元 4 主要激活于 LP 阶段，该协同元的提前激活可以为冲拳提供更好的发力支撑。这表明运动水平的提升可以通过提前激活肌肉协同来提高效率。4）在肌肉权重方面，协同元 2 中专业组比初学者组的左侧股直肌激活水平更高（$p<0.05$）。在协同元 4 中，专业组比初学者组的右侧腹直肌激活水平更高（$p<0.05$），左侧臀大肌的激活水平更低（$p<0.05$），表明专业运动员在动作转换时能更迅速地启动“核心-上肢”协同模块。**研究结论：** 跃步冲拳时专业组提取出 5 组肌肉协同，而初学者组仅存在 4 组肌肉协同，并且运动水平的提升通过调整落地仆步和弓步冲拳时肌肉协同的时间结构、动态调节落地仆步时左侧股直肌以及弓步冲拳时核心肌群与臀肌的相对权重，优化运动模式。在实际应用中，可以利用肌肉协同数量、组合协同的数量、激活时序等指标评估技能水平，在训练中可以通过强化核心和上肢的协同作用、增加骨盆稳定性等方法，提升动作质量。

关键词：武术；肌肉协同；运动水平；跃步冲拳

Muscle Synergy Characteristics of the Leaping Step Punch Motion and Analysis of Performance Level Differences

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Objective: Wushu is an important component of traditional Chinese sports culture. As one of the fundamental routines in the youth boxing, the Leaping Step Punch helps establish movement memory aligned with the principles of Wushu practice. This technique incorporates multiple fundamental Wushu movements and requires coordinated involvement of joints and muscle groups across the entire body in both time and space. Its execution quality is closely related to neuromuscular control capabilities. Research indicates that during motor tasks, the central nervous system can coordinate multiple muscle groups by activating functional modules. This partten of muscle synergy has become an important method for studying motor skill learning and enhancement, although muscle synergy effects may vary with skill level. However, most existing Wushu studies predominantly focuses on the characteristics of individual muscles, and the underlying neuromuscular control mechanisms remain poorly understood. Therefore, this study aims to compare the differences in muscle synergy characteristics between a professional group and a novice group during the execution of the leap-step punch movement. It provides an in-depth analysis of the underlying neuromuscular control mechanisms. This research not only establishes a theoretical foundation for enhancing motor skills and scientific training but also offers athletes and coaches a quantitative basis for standardising movement execution. **Methods:** This study recruited 22 male university students. They are divided into a professional group (n=11, Wushu majors, height 181.75±1.35 cm, weight 75.75±2.15 kg, with 2.91±0.19 years of specialized Wushu training) and a novice group (n=11, height 183.25±2.57 cm, weight 75.25±3.22 kg). All participants had no history of sports injuries or surgical procedures within the preceding six months. The professional group should have undergone at least two years of systematic martial arts training, training at least three times weekly, and demonstrated technically proficient execution. The novice group had not received systematic specialist Wushu training but possessed prior experience in Wushu coursework. Kinematic characteristics of the leaping step punch movement were captured using a Vicon three-dimensional motion capture system (sampling frequency 200Hz, Oxford, UK). Three Kistler three-dimensional force plates (1 kHz, 9286 AA, 100.0 cm × 30.0 cm × 0.5 cm, Waalwijk, Switzerland) embedded in the floor measured ground reaction forces at the ground contact and take-off moments of the leaping step punch, enabling motion phase segmentation. Concurrently, a Delsys wireless surface electromyography (EMG) system recorded signals from 16 muscles (encompassing bilateral lower limbs,

dominant-side trunk, and upper limb muscle groups). The subject first performs a 10-minute warm-up. Following completion, the target muscle belly is cleaned with alcohol and surface electromyography sensors are affixed. The subject stands 20cm in front of the force platform, performing a leap-punch strike from a standard starting stance (balancing on the right leg with the left knee flexed at 90° and raised, arms in Wushu starting posture). Left foot lands, then pushes off to leap upward. Right leg swings forward and lands. Subsequently, the left leg extends forward while the body pivots right, simultaneously lowering the centre of gravity to transition into a right crouch stance. Once the crouch stance stabilises, it shifts into a left lunge to execute the thrust punch. Based on movement characteristics and kinematic and kinetic features, the action is divided into three phases: Leap-Flight (LF), Crouch-Landing (CL), and Lunge-Punch (LP). Kinematic and kinetic data are calculated by Visual 3D software. They are smoothed using a 4th-order low-pass Butterworth filter with cutoff frequencies of 10 Hz and 50 Hz. Preprocessing of EMG data involved high-pass filtering using a fourth-order zero-phase IIR Butterworth filter with a cutoff frequency of 50Hz. Subsequently, full-wave rectified EMG signals underwent low-pass filtering with a fourth-order Butterworth filter at 20Hz to derive a linear envelope. The preprocessed EMG data undergoes non-negative matrix factorisation (NMF) using the classical Gaussian NMF algorithm. This decomposes the EMG data matrix E into a motor modules matrix W and a motor primitives matrix H, with E reconstructed as Er. The coefficient of determination R^2 is used to evaluate the quality of NMF reconstruction. A linear regression model is applied to fit R^2 against the number of muscle synergies (r), and the number of synergies corresponding to the point of maximum slope on the fitted curve is selected as the optimal number. The k-means algorithm is then applied to cluster the synergistic muscle activity for all subjects within each group. To compare activation characteristics of muscle synergies across different movement phases, the center of activity (CoA) and full width at half maximum (FWHM) of the motor primitives (matrix H) are calculated for each group. Data analysis is performed using SPSS 26.0. Independent samples t-tests are used for data passing normality tests; otherwise, non-parametric tests are applied. The significance level is set at 0.05. **Results:** 1) The professional group exhibited five muscle synergies during the leap-step punch, while the novice group only showed four. Synergy 5 was unique to the professional group, primarily activated during the LP phase, indicating high coordination between upper limb muscles and gluteal muscles. This suggests that professionals can enhance the explosiveness and precision of the punch on a more stable pelvic base. The increase in synergies not only reflects the central nervous system's ability to regulate complex tasks but may also indicate the development of higher-level movement structure and coordination strategies. 2) Although the proportion of combined synergies between the professional and novice groups showed no significant difference ($p > 0.05$), the professional group exhibited a relatively lower proportion. This suggests that as athletic proficiency increases, the structure of muscle coordination may become more refined, reducing redundant synergistic activation. 3) Regarding activation timing structures, significant differences in CoA were observed between the professional and novice groups for Synergy 3 ($p < 0.01$) and Synergy 4 ($p < 0.05$). The professional group activated these muscle synergies earlier. Synergy 3 primarily activated during the CL phase. Its earlier activation reduces the force generation time required for transitioning from a lunge to a lunge stance. Synergy 4 primarily activated during the LP phase. Its earlier activation provided superior force support for the punch. This indicates that enhanced athletic proficiency can improve efficiency through earlier synergistic muscle activation. 4) Regarding muscle weights, the professional group exhibited higher activation levels in the left rectus femoris within synergy 2 compared to the novice group ($p < 0.05$). In Synergy 4, the professional group exhibited higher activation levels in the right rectus abdominis ($p < 0.05$) and lower activation levels in the left gluteus maximus ($p < 0.05$) compared to the novice group. This indicates that professional athletes can more rapidly activate the ‘core-upper limb’ synergy module during movement transitions. **Conclusion:** This study compared muscle coordination patterns during the Wushu leaping step punch movement between a professional group and a novice group. It was found that the professional group exhibited five sets of muscle coordination, whereas the novice group exhibited only four. Furthermore, enhancing athletic performance can be achieved by dynamically adjusting the temporal structure of muscle synergies during the landing lunge and bow-stance punch phases. This involves optimising the relative weighting of the left rectus femoris during the landing lunge and the core muscles alongside gluteal muscles during the bow-stance punch, thereby refining the movement pattern of the martial arts lunge punch. In practical application, skill proficiency may be quantified through metrics such as synergistic muscle count, proportion of combined synergies, and activation sequencing. Training interventions may enhance technique quality by guiding core muscle activation prior to landing, thereby strengthening core-upper limb coordination, increasing pelvic stability, and improving the execution of the martial arts lunge punch.

Keywords: Wushu; Muscle Synergy; Performance Level