Multi-joint Cooperative Control of Athletes under High Intensity Training

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Abstract: The control structure and performance of high intensity sports training on the trunk joint of athletes is analyzed to improve the quality of sports training, a multi-joint cooperative control model for athletes under high intensity sports training is proposed based on attitude sensor fusion tracking compensation. The multi-joint kinematics model of the athletes' torso under high intensity sports training is constructed, and the constraint parameters of the multi-joint linkage and cooperative control of the athletes are analyzed combined with the identification method of the parameters of the state space model. The mechanical control model of the action of high intensity sports training on athletes' torso is established by using the coupling method of driving branch chain inertia, and the characteristics of multi-joint linkage coupling of athletes are analyzed. The collaborative filtering Kalman fusion method is used to realize the parameter fusion and adaptive parameter identification of athletes' multi-joint linkage. According to the results of parameter recognition, athletes' multi-joint linkage collaborative control is realized. The simulation results show that the high intensity sports training method has good stability and low error of attitude parameter adjustment for athletes' multi-joint linkage and coordination control, which improves the effect of sports training.

1. Introduction
In the multi-disciplinary development of human kinematics and control science, the intelligent control analysis model is used to analyze human motion science, and the control model of human motion is constructed by combining the study of human motion dynamics and kinematics modeling. To realize the level of scientific guidance to human movement, under the mode of high intensity sports training, the control model of the trunk joint of athletes is analyzed, and the research on the coordinated control of multi joint linkage of athletes by high intensity sports training is carried out. This paper analyzes the mechanical relationship and characteristics of high intensity sports training on the trunk and joints of athletes, and uses the methods of feature extraction and statistical analysis to model and analyze the dynamics in the process of human body movement[1]. In order to improve the ability of high intensity sports training to control the multi-joint linkage and coordination of athletes, and according to the control results to achieve physical training guidance, the research on the relevant control methods has been paid great attention.

Based on the analysis of sports mechanics characteristics and the sampling of parameters, the research on the coordination control of athletes' multi-joint linkage in high-intensity sports training needs to analyze the constraint parameters of multi-joint coordination in athletes' torso under high-intensity sports training[2]. This paper describes the problem of multi-joint coordination control under high intensity sports training as a multi-dimensional mechanical control model, which combines
mechanical parameter analysis and information fusion technology to realize the multi-joint linkage and coordination control of athletes\textsuperscript{3}. Among them, a multi-joint linkage cooperative control method based on adaptive terminal synovial control is proposed in reference [4]. The buffeting suppression problem of multi-joint coordination in athletes’ torso under high intensity sports training is transformed into a multi-constraint motion planning problem in high-dimensional C-space, which can effectively realize the kinematics control of human body, but this method has a large amount of computation. Real-time control performance is poor. In reference [5], a multi-joint cooperative attitude control model based on inertial attitude space adjustment is proposed, which combines attitude inertial parameter adjustment method for fuzzy control. However, the proposed method has large ambiguity and poor adaptive performance. In order to solve these problems, this paper proposes a cooperative control model based on attitude sensor fusion and tracking compensation for multi-joint linkage of athletes in high-intensity sports training. Firstly, the multi-joint kinematics model of the athletes’ torso under high intensity sports training is constructed, and the constraint parameters of the multi-joint linkage and cooperative control of the athletes are analyzed with the method of identifying the parameters of the state space model. Then, the mechanical control model of the action of high intensity sports training on athletes’ torso is built by using the coupling method of driving branch chain inertia, and the characteristics of multi-joint linkage coupling of athletes are analyzed. According to the result of parameter recognition, the multi-joint coordinated control of athletes is realized. Finally, simulation experiments are carried out to show the superior performance of this method in improving the ability of multi-joint linkage and cooperative control of athletes.

2. Constraint parameters and dynamic model of multi-joint coordinated control of athletes

2.1. Construction of multi-joint kinematic model

Aiming to realize the optimal control of multi-joint linkage cooperative control by high-intensity sports training, the kinematics and dynamics parameters model of high-intensity sports training for athletes’ multi-joint linkage collaborative control is constructed firstly\textsuperscript{4}. The multi-joint kinematics model of athletes' torso under high intensity sports training is constructed, and the constraint parameters of multi-joint linkage and cooperative control of athletes are analyzed with the method of identifying the parameters of state space model. The dynamic equations of attitude configuration parameter identification are constructed as:

\[
\begin{align*}
    \dot{m\vec{v}} &= -mg \sin \theta - c q S_{\omega} + P \\
    m\vec{v} \theta &= -mg \cos \theta + c q S_{\omega} + P(\alpha + \delta_\phi) + m_l \ddot{\phi}_\alpha \\
    J_\phi \phi &= -c q S_{\omega} (x - x_t) \alpha - q S_{\omega} m_l \frac{l_1}{V} \\
    J_\phi \delta_\phi &= -P(x - x_t) \delta_\phi - m_l \ddot{l}_1 \delta_\phi - m_\alpha \ddot{\alpha}_\phi (x - x_t) - J_\phi \delta_\phi
\end{align*}
\]

(1)

Wherein, the motion variables describing the multi-joint track at the end of the torso under high intensity sports training are $\phi$, $\dot{\phi}$, $\alpha$, $\dot{\alpha}$, $\theta$, $\dot{\theta}$, and so on; and under the condition that the input variable of the multi-joint control in the trunk is determined under high intensity sports training, the state variable $x_0 = [\phi_0, \dot{\phi}_0, \theta_0]^T$ of the output stability feature functional is modified according to the measurement error, and the equilibrium condition of the dynamic coupling characteristics of the athletes’ torso under high intensity sports training is obtained. The dynamic coupling characteristic equilibrium condition of the athlete’s torso is obtained: $f(x_0, u_0) = 0$. According to the changing rule of motion track, it is obtained that the state quantity of multi-joint adjustment in the trunk of athletes under high intensity sports training is $x = [\phi_0 + \Delta \phi, \dot{\phi}_0 + \Delta \dot{\phi}, \theta_0 + \Delta \theta]^T$, $\delta_\phi = \Delta \delta_\phi$. As a result, the linearized small disturbance equation for the end trajectory planning of the multi-joints of the athletes’ torso under high intensity sports training is obtained as follows:
According to the above-mentioned equations, the dynamic mathematical model of multi-joints of athletes' torso under high intensity sports training is analyzed. The actual coupling force moment mathematical model of active branched chain is described as follows:

\[
\begin{align*}
\mathbf{mV} & \Delta \dot{\mathbf{\theta}} = (c_1^2 q_S \mathbf{u} + P) \Delta \mathbf{\alpha} + mg \sin \theta \Delta \mathbf{\theta} + P \Delta \mathbf{\varphi} + m_g \Delta \mathbf{\delta}_e + F_g, \\
J_\alpha & \Delta \dot{\mathbf{\phi}} = -c_2^2 q_S \mathbf{u}(x_e - x_r) \Delta \mathbf{\alpha} - q_S m_g \frac{d^2}{dt^2} \Delta \mathbf{\dot{\phi}} + V - P(x_e - x_r) \Delta \mathbf{\delta}_e - m_g \frac{d}{dt} \Delta \mathbf{\delta}_e - m_g \Delta \mathbf{\dot{\delta}_e}(x_e - x_r) - J_\alpha \Delta \mathbf{\dot{\delta}_e} + M_g.
\end{align*}
\]

\[
(2)
\]

According to the above-mentioned equations, the dynamic mathematical model of multi-joints of athletes' torso under high intensity sports training is analyzed. The actual coupling force moment mathematical model of active branched chain is described as follows:

\[
\begin{align*}
\Delta \dot{\mathbf{\theta}} &= c_1 \Delta \mathbf{\alpha} + c_1 \Delta \mathbf{\theta} + c_1' \Delta \mathbf{\delta}_e + c_1' \Delta \mathbf{\dot{\delta}_e} + F_g, \\
\Delta \dot{\mathbf{\phi}} &= b_1 \Delta \mathbf{\dot{\phi}} + b_1 \Delta \mathbf{\alpha} + b_1' \Delta \mathbf{\delta}_e + b_1' \Delta \mathbf{\dot{\delta}_e} = \Omega_g, \\
\Delta \mathbf{\dot{\delta}_e} &= \Delta \mathbf{\dot{\theta}} + \Delta \mathbf{\dot{\alpha}}
\end{align*}
\]

\[
(3)
\]

Where, \( c_1 = \frac{1}{mV} (57.3 c_1^2 q_S \mathbf{u} + P) \), \( c_2 = \frac{1}{V} g \sin \theta \), \( c_3 = \frac{P}{mV} \), \( b_1 = \frac{57.3}{J_\alpha V} m_g q_S m_g^2 l^2 \), \( b_2 = \frac{57.3}{J_\alpha} c_2^2 q_S \mathbf{u}(x_e - x_r) \), represents the known coefficients of the model and the kinetic energy and potential energy of multi-joint motion in the trunk of athletes under high intensity physical training, respectively. According to the above analysis, the mechanical control modeling of the action of athletes' torso by high intensity sports training is carried out by using the coupling method of driving branch chain inertia[7].

2.2. Control constraint parameter analysis

The technique of fusion tracking and fuzzy recognition is used to collect the attitude parameters of athletes in the process of multi-joint linkage and cooperative control through high-intensity sports training. Firstly, the adaptive pose kinematics model is used to construct the mathematical model of motion planning constraint parameters of the multi-joints in the torso under high intensity sports training. There are many factors to be considered in the control design of the multi-joints of the athletes' torso[8]. The output mechanics of multi-joints of athletes' torso has linear characteristics under high intensity sports training. The spatial planning model is constructed by linear model, which includes the adjustment of configuration spatial parameters and the design of motion planning under the condition of high intensity sports training. The attitude and configuration parameters are identified and the distance measurement is carried out. The adaptive attitude parameter adjustment method is used to simulate the posture of multi-joints of athletes' torso under high intensity sports training, which can effectively meet the demand of pose disturbance correction under high intensity sports training. In the high-dimensional C-space, the probability distribution model of dynamic characteristics distribution of athletes' torso multi-joints under high-intensity sports training is constructed. The kinematic chain model SFS and three-dimensional rotational degrees of freedom \( \{ A^b, A^d \} \) are used to describe the spatial motion planning model of the multi-joints of the athletes' torso in the process of terminal trajectory motion under high intensity sports training. The control constraint parameter model of multi-joint cooperative chattering suppression of athletes' torso is obtained. In this paper, the forward kinematics (FK) equation is used to express the inverse state equation of the end effect of the multi-joints in the athletes' torso under high intensity sports training. In the motion inertia coordinate system \( \mathbf{q}_0 = [\alpha_0, \beta_0, \gamma_0, \theta_1, \theta_2, \theta_3] \), the results are as follows:

\[
0^T_n(\mathbf{q}_i) = \prod_{i=0}^{n-1} (i^{-1})^T(\mathbf{q}_i) = \begin{bmatrix} n & o & a & p \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

\[
(4)
\]

Under high intensity sports training, the motion state constraint parameter \( 0^T_4 \) of the multi-joints in the trunk of the athlete's trunk at the end of the sport is as follows:

\[
0^T_4 = \prod_{i=4}^{4} (i^{-1})^T(\mathbf{q}_i) = \begin{bmatrix} n_4 & o_4 & a_4 & p_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}
\]

\[
(5)
\]
Where, \( \mathbf{a}_4 = \mathbf{r}_w - \mathbf{p}_4 / \| \mathbf{r}_w - \mathbf{p}_4 \| \), \( \mathbf{r}_w = \mathbf{p} - l_h \cdot \mathbf{n}_4 \), \( \mathbf{o}_4 = \mathbf{a}_4 \times \mathbf{(r}_w - \mathbf{p}_4) / \| \mathbf{a}_4 \times \mathbf{(r}_w - \mathbf{p}_4) \| \), \( \mathbf{n}_4 = \mathbf{o}_4 \times \mathbf{a}_4 \).

Under high intensity sports training, the initial configuration of the multi-joints of the athlete's trunk in the longitudinal motion space relative to the geodetic coordinate system is \( \theta_{\text{start}} = [\theta_{\text{start}}, \ldots, \theta_{\text{start}}]^{T} \). In the motion space planning, the two-degree-of-freedom model is used to adjust the parameters, and the target position is \( \mathbf{p}_{\text{obj}} \in \mathbf{R}^6 \), \( \mathbf{q}_1 = [\mathbf{q}_1, \ldots, \mathbf{q}_7]^{T} \equiv [\theta_4, \ldots, \theta_6]^{T} \), respectively. Based on the above analysis, adopts inertial attitude simulation and adaptive error adjustment method to construct an adaptive attitude kinematics model. Under the condition of high intensity sports training, the problem of motion planning in multi-joint cooperative operation of athletes' torso is transformed into the optimization control problem in seven degrees of freedom motion space, and the analysis of motion dynamics is carried out in combination with the control constraint parameter model. Improve the ability of multi-joint cooperative control[9].

3. Control model optimization

3.1. Analysis of dynamic Coupling intensity of multiple joints in athletes' torso

On the basis of the above-mentioned multi-joint kinematics model and control constraint parameter analysis of athletes' torso under high intensity sports training, the multi-joint linkage collaborative control model optimization of athletes is carried out. In this paper, a cooperative control model based on attitude sensor fusion and tracking compensation for multi-joint linkage of athletes in high intensity sports training is proposed. The attitude parameter fusion of flexible mechanics is carried out by Kalman filtering method, and the error parameters and inertial attitude parameters of the trajectory correction of athletes' torso multi-joint end under high intensity sports training are obtained:

\[
T = \frac{1}{2} M_{LL} X_{LL}^2 + \frac{1}{2} M_{RR} X_{RR}^2 + \frac{1}{2} J_{LL} \theta_{LL}^2 + \frac{1}{2} J_{RR} \theta_{RR}^2 + \frac{1}{2} M_{p}[(\theta_{p} \cos \theta_{p} + X_{RM})^2 + (-\theta_{p} \cos \theta_{p})^2] + \frac{1}{2} J_{p\theta} \theta_{p}^2 + \frac{1}{2} J_{p\delta} \delta^2 \quad (6)
\]

\[
V = M_{p} g L \cos \theta_{p} \quad (7)
\]

The joint cooperative control problem is transformed into a multi-constrained motion planning problem in high-dimensional C-space, which is selected in the reference plane of multi-joint cooperative motion in the zero potential energy surface[10]. The mechanical control model of the action of high intensity sports training on athletes' torso is modeled by the coupling method of each driving branch chain. The dynamic coupling model between the active branched chains is obtained as follows:

\[ P_{m} = C_L \theta_{RL} + C_R \theta_{RR} - (C_L + C_R) \theta_{p} \quad (8) \]

The adaptive terminal synovial control method is used to suppress the buffeting of athletes' torso multi-joints under high intensity sports training, combined with the constraint conditions. We can obtain three equations of state of synovial membrane under high intensity sports training for the cooperation of multiple joints in the torso of athletes:

\[ (M_{RL} R^2 + J_{RL} + \frac{1}{4} M_{p} R^2 + \frac{R^2}{D^2} J_{PS}) \tilde{\theta}_{RL} + \left( \frac{1}{4} M_{p} R^2 - \frac{R^2}{D^2} J_{PS} \right) \tilde{\theta}_{RR} + \frac{1}{2} M_{p} R L \tilde{\theta}_{p} = C_L \quad (9) \]

The variation of coupling characteristics with structural parameters is analyzed. \( X_{RM}, V_{RM}, \theta_{p}, \omega_{p}, \delta, \dot{\delta} \) are used to represent the matching parameters of multi-joint load inertia of athletes' torso under high intensity sports training, and the eigenvalues of structural inertia are considered. The characteristics of multi-joint linkage coupling in the multi-joint state space of athletes' torso are obtained.
3.2. cooperative control law

The collaborative filtering Kalman fusion method is used to realize the parameter fusion and adaptive parameter identification of athletes' multi-joint linkage, and the collaborative control of athletes' multi-joint linkage is realized according to the result of parameter recognition. The end sliding surface equation of multi-joints of athletes' torso under high intensity sports training is described as follows:

Under high intensity sports training, the state term $\delta$, $\delta$ and the state $x_{RM}, v_{RM}, \theta_P, \omega_P$ of the multi-joints of the athletes' torso are independent of each other. The inverse control method is used to compensate the state and adjust the terminal trajectory adaptively. The output control state equation of multi-joint cooperative suppression of athletes' torso is obtained as follows:

$$
\begin{bmatrix}
\dot{x}_m \\
\dot{v}_m \\
\dot{\theta} \\
\dot{\omega}
\end{bmatrix} =
\begin{bmatrix}
0 & 1 & 0 & 0 & 0 & 0 \\
0 & -2K_mK_b/R & a_{23} & 2K_mK_b & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 \\
0 & -2K_mK_b/R & a_{43} & 2K_mK_b & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
x_m \\
v_m \\
\theta \\
\omega
\end{bmatrix} +
\begin{bmatrix}
0 \\
K_mK_b \\
K_mK_b \\
K_mK_b
\end{bmatrix}
\begin{bmatrix}
U_L \\
U_R
\end{bmatrix}
$$

According to the coupling characteristic quantity of athletes' multi-joint linkage, the method of collaborative filtering Kalman fusion is used to realize the fusion of athletes' multi-joint linkage parameters, and the inertial motion equation under generalized coordinates is obtained as follows:

$$
\begin{align*}
\dot{x}_1 &= x_3 \\
\dot{x}_2 &= f_\theta(X,t) + g_\theta(X,t)u(t) + d_\theta(t) \\
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= f_s(X,t) + g_s(X,t)u(t) + d_s(t)
\end{align*}
$$

Where, $X=[\theta, x, \dot{x}, \ddot{x}]^T$, $f_s(X,t)$, $f_\theta(X,t)$, $g_s(X,t)$, $g_\theta(X,t)$, represents the inertia matrix in joint space respectively, and constructs the Lyapunov function $V_s = \frac{1}{2}S^2(t)$, and the dynamic coupling characteristic section is carried on, then:

$$
\begin{align*}
\dot{V}_s &= S(t)S(t) = S(\lambda\dot{\lambda}_s\dot{\lambda}_s + \lambda\dot{\lambda}_g\dot{\lambda}_g + \lambda\dot{\lambda} + \dot{\lambda}_\theta) = S(\lambda\dot{\lambda}_s\dot{\lambda}_s + \lambda\dot{\lambda}_g\dot{\lambda}_g + \lambda\dot{\lambda}_s + \lambda\dot{\lambda}_g = (g_\theta + \dot{\lambda}_s^2)(-f_\theta - \dot{\lambda}_g\dot{\lambda}_g + \dot{\lambda}_s + \dot{\lambda} + \dot{\lambda}_s + \dot{\lambda}_g)
\end{align*}
$$

The above formula shows that the adaptive terminal synovial control process of multi-joints in the torso of athletes under high intensity sports training is steady-state convergence, in order to reduce the error interference. Improve the sports stability of multi-joints in the trunk of athletes under high intensity sports training.

4. Simulation experiment and result analysis

In order to verify the application performance of this method in the collaborative control of athletes' multi-joint linkage under high intensity sports training, the experimental analysis is carried out. The experimental motion model is built in the follow-up coordinate system Oxyz, and the simulation tool is
Matlab7. The coupling characteristic of athletes' multi-joint linkage is 0.45, and the setting of main parameter variables is shown in Table 1.

| Parameter name                        | Short-cut process |
|---------------------------------------|-------------------|
| Coupling moment                       | 56.8 KN.m         |
| Inertial attitude adjustment modal parameters | 1400 N·m/rad     |
| Curve smoothing coefficient            | 0.43              |
| Natural frequency                     | 66K Hz            |
| End moment of main arm                 | 345KN             |
| Step response of simulated training    | 0.32              |
| Coupling characteristic quantity       | 3.45              |

According to the above simulation environment and parameter setting, the multi-joint coordinated control model of athletes with high intensity sports training is analyzed, and the multi-joint cooperative control simulation of torso is carried out under two kinds of motion states of square rotation and forward rotation, respectively. The action demonstration is shown in figure 1.

![Action Demonstration](image)

(a) internal state of charge  (b) Abduction state

Figure 1. Movement action demonstration of high-strength sports training

The mechanical control model of high intensity sports training on athletes' torso is established by using the coupling method of driving branched chain inertia. The joint control moments of the main arm and the slave arm are obtained, and the results are shown in figure 2.

![Joint Control Moment](image)

Figure 2 Joint control moment

The analysis of figure 2 shows that this method can be used to calculate the mechanical parameters of the multi-joints of the athletes' torso effectively, and the calculation results are accurate and reliable. In order to test the control convergence of the method in this paper, the performance of the control curve is shown in figure 3. The results of fig. 3 show that the convergence of the proposed method is good and the robustness of the control model is high.
5. Conclusions
In the mode of high-intensity sports training, the control model of the trunk joint of athletes is analyzed, and the mechanical relationship and characteristics of the action of high-intensity sports training on the trunk and joints of athletes are analyzed. In this paper, a cooperative control model based on attitude sensor fusion and tracking compensation for multi-joint linkage of athletes in high intensity sports training is proposed. The pose simulation of multi-joints in the trunk of athletes under high intensity sports training is carried out by using the adaptive attitude parameter adjustment method, and the multi-joint kinematics model of the trunk of athletes under high intensity sports training is constructed. Combined with the parameter identification method of state space model, the dynamic analysis is carried out to realize the coordinated control of multi-joint linkage of athletes. The results show that the cooperative control of athletes' torso under high intensity sports training has high stability and good convergence, and it has a good application guidance value in athletes' physical fitness training.

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