Impedance-Controlled Knee Orthosis: Transitional Movements and their Effect on Knee Kinematics and Muscular Activity

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Motivation



- **Low-Cost Rehabilitation**: Integrating existing rehabilitation equipment, which is CE-certified, with off-the-shelf parts to provide active devices
- **Personalized User Interaction**: Fine-Tuning support to patients' needs in different clinical settings and adapting the assistance over time.
- **Proportional Control**: Exploring direct control in lower limb exoskeletons to enable more intuitive interaction and shorter learning curves for users.

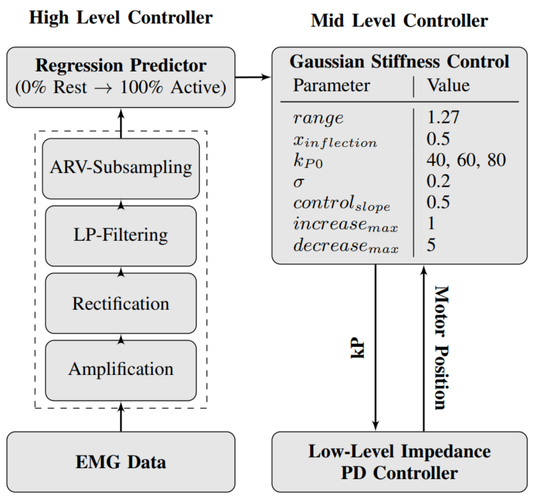
[1,2,3]

Methods

A. Experimental Setup

- 8 Trigno® Avanti sEMG sensors (Delsys Inc.), streaming data at 2148 Hz.
- Two sensors were placed on the extensor and flexor muscles of each leg: Rectus Femoris, Vastus Lateralis, Biceps Femoris, and Semitendinosus
- **Signal Processing** involved amplification and rectification, a Low-Pass Filter at 1Hz cut-off frequency, and subsampling at 50 Hz, handled by a C# application.
- An **Incremental Ridge Regression** method was employed for real-time control, trained initially on the subject's signals. Range: 0 (rest) to 1 (MVC)

[4,5,6]



B. Control Strategies

Impedance Controller (dynamic $k_P, k_D = 0.3$) + Custom Mid-Level-Control:

- Gaussian-Based Stiffness Calculation
  - μ motion range midpoint, shifting peak via $\boldsymbol{x_{inflection}}$
  - **σ** determines the spread of the Gaussian

$$\mu = \frac{range}{2} * \left(1 + x_{inflection}\right)$$

$$k_P(\theta) = k_{P,0}\, exp\left(-\frac{(\theta-\mu)^2}{2\sigma^2}\right)$$

- Scaling Factor & EMG Control signal Influence
  - $control_{slope}$ shapes the gradient from μ. High values cause sharper stiffness decay (or increase), providing a steeper gradient.
  - $control_{EMG}$ linear scaling

$$k_{P,scale} = k_P(\theta)\left(\frac{\theta}{\mu}\right)^{control_{slope}}$$

$$k_{P,final} = k_{P,scaled} \times control_{EMG}$$

- Ramping Logic & Boundary Conditions
  - Limit the rate of stiffness change between consecutive calculations to ensure smooth transitions and prevent abrupt changes in stiffness.
  - Clamp values to non-negative values

$$\Delta k_{P,increase} = k_{P,prev} + increase_{max}$$

$$\Delta k_{P,decrease} = k_{P,prev} - decrease_{max}$$

$$k_{P,final} = \max\left(0, k_{P,final}\right)$$

C. Experimental Protocol

- 4 Able-bodied Participants
- Each participant completed five repetitions of Sit-To-Stand and Step-Up Tasks under five different conditions:

Without Orthosis, Orthosis Off, Orthosis ON (k_P=40,60,80)

[7]

Results

A. Overall ARV Reduction:

- Evaluation of the normalized muscle activity across all participant during the full Sit-To-Stand, suggests a significantly decreased muscle activity in the extensor muscles of the assisted leg (right).
- Compared to the non-assisted leg (left), the ARVs are reduced slightly (≈ 10%),

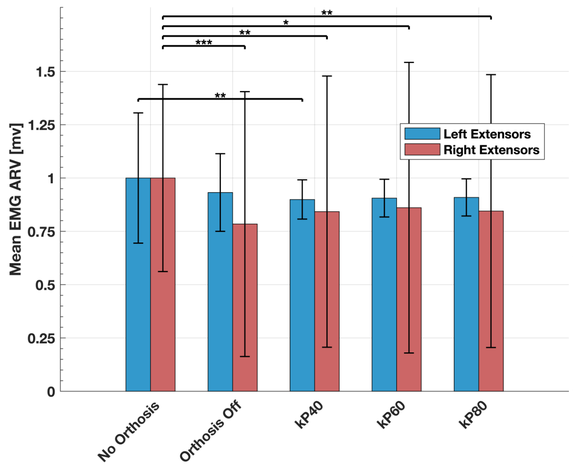
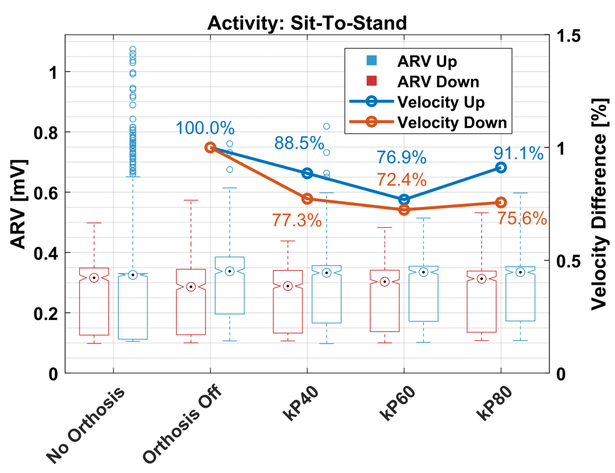


TABLE IV
SIGNIFICANCE ANALYSIS (P-VALUES) FOR SIT-TO-STAND AND STEP-UP ACROSS DIFFERENT STIFFNESS GAINS BY SIT-TO-STAND UP-PHASE (P1) AND STAND-TO-SIT DOWN-PHASE (P2). SHOWN ARE GLOBAL VALUES FOR VELOCITY AND ARV.

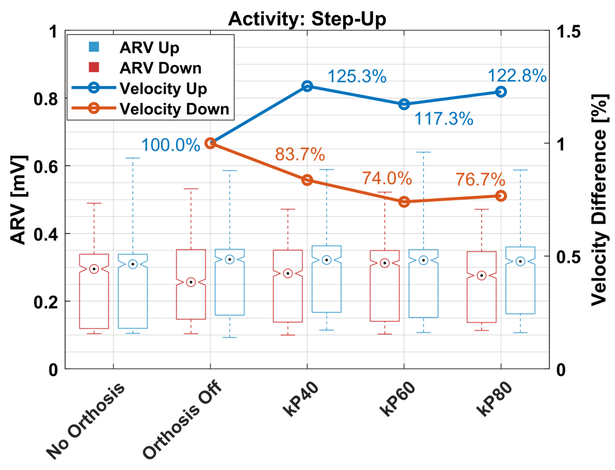
	Sit-to-Stand				Step-Up			
	Velocity		ARV		Velocity		ARV	
Mode	P1	P2	P1	P2	P1	P2	P1	P2
k_{P40}	0.0053	0.0029	$< 10^{-10}$	0.11	0.656	0.025	$< 10^{-6}$	$< 10^{-6}$
k_{P60}	0.0120	0.0042	$< 10^{-8}$	0.10	0.6556	0.0696	0.0005	0.0000
k_{P80}	0.05	0.01	$< 10^{-5}$	0.12	1.000	0.40	0.0000	0.0000

B. Up- vs. Down-Phase

- During the **Up-Phase** of ***Sit-to-Stand***, the velocity reduction was less consistent (around 9–13%). Yet, the average rectified values (ARVs) increased by up to 13% under orthosis assistance, while the **Down-Phase** ARVs remained closer to baseline. Statistical tests confirmed that the velocity and ARV differences in the Up-Phase were significant when comparing idle conditions to higher stiffness gains. In contrast, the ARV changes in the Down-Phase were not statistically significant.



- For the ***Step-Up*** activity, orthosis assistance increased **Up-Phase** velocity by up to 25% and decreased **Down-Phase** velocity by up to 26%, with the descending movement showing more significant changes. In the Step-Up, ARV medians in the Up-Phase were slightly higher than baseline, while the Down-Phase consistently showed lower ARVs, highlighting the distinct impact of orthosis stiffness on ascending versus descending movements.



Discussion & Conclusion

- **Reduced muscle activity** with approximately 37% torque offloading, providing augmentation rather than full compensation of user effort.
- **Stable tasks**, like Sit-to-Stand, **showed limited benefits**, while **unstable tasks**, such as Step-Up, **responded more clearly** to the assistance.
- The study's exploratory design highlighted the **need for better control strategies, hardware adjustments, and user-specific tuning** for broader clinical applications.

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