A novel 7 degrees of freedom model for upper limb kinematic reconstruction based on wearable sensors

L.Peppoloni, A. Filippeschi, E. Ruffaldi, C. A. Avizzano
{l.peppoloni, a.filippeschi}@sssup.it

PERCRO Perceptual Robotics Laboratory

ISTITUTO DI TECNOLOGIE DELLA COMUNICAZIONE, DELL'INFORMAZIONE E DELLA PERCEZIONE — Scuola Superiore Sant'Anna

We present a **novel 7 DoFs model** representing a trade-off between modeling accuracy and complexity for the human upper limb. We model the human shoulder girdle taking into account also humerus head's elevation and retraction due to scapula's and clavicle's motions.

Context and Goal:

- Ecological detection of work related pathologies for workers in unstructured environments:

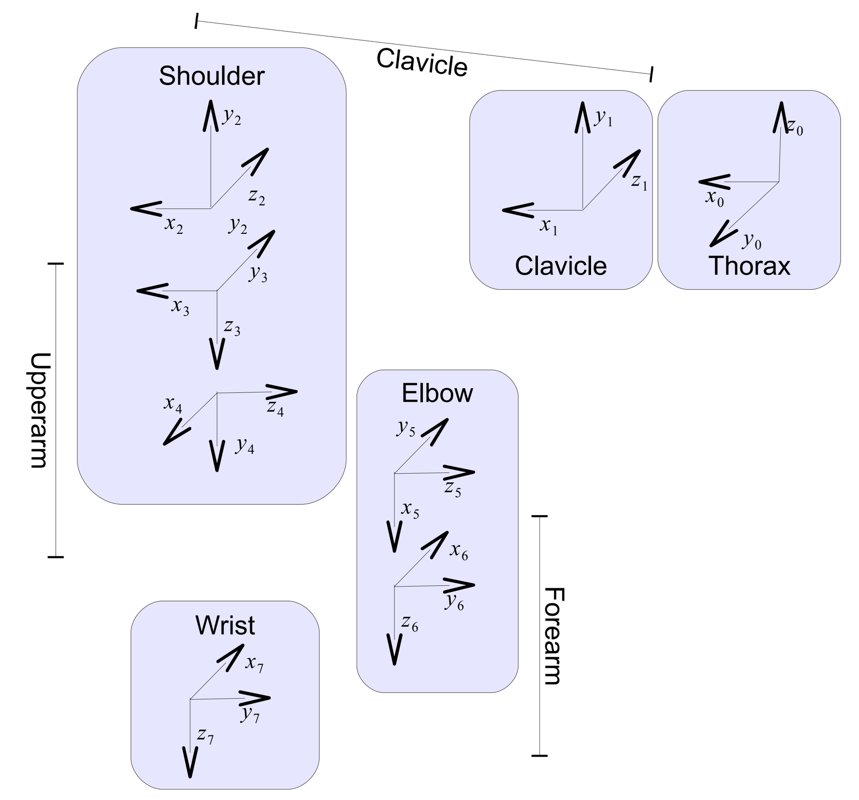
Pathologies causes :

- Repetitive actions with dangerous postures and loads

- System for tracking and analysis of workers in ecological conditions
- Motion estimated from inertial sensors
- Grasp force estimation by surface EMG matrix (in progress)

The kinematic Model

- 7 DoFs model parametrized according to DH convention
- Starting from the analysis in [1] we modeled the shoulder girdle with 5 DoFs
  - 2R centered on the clavicle for scapular protraction/retraction and elevation/depression
  - 3R for shoulder abduction, rotation and flexion
  - 2R for elbow flexion and pronation/supination
- Sensors
  - Orientation relative to their parent limb frame represented with Euler's angles
  - Parameters from: $\min_{\gamma,\beta,\phi} \|R_0^s(\gamma,\beta,\phi)g^0 - \ddot{x}_s^s\|$



Frame	a_i	α_i	d_i	ϑ_i	Joint
1	0	$\pi/2$	0	ϑ_1	Scapula Protraction
2	l_{cl}	$\pi/2$	0	ϑ_2	Scapula Elevation
3	0	$\pi/2$	0	ϑ_3	Shoulder Abduction
4	0	$\pi/2$	0	$\vartheta_4 - \pi/2$	Shoulder Rotation
5	l_{ua}	0	0	$\vartheta_5 + \pi/2$	Shoulder Flexion
6	0	$\pi/2$	0	$\vartheta_6 + \pi/2$	Elbow Flexion
7	0	0	l_{fa}	ϑ_7	Elbow Rotation

State Model

$$x_i = \left[\vartheta_i, \dot{\vartheta}_i, \ddot{\vartheta}_i\right]^T \qquad i = 1, \dots, 7$$

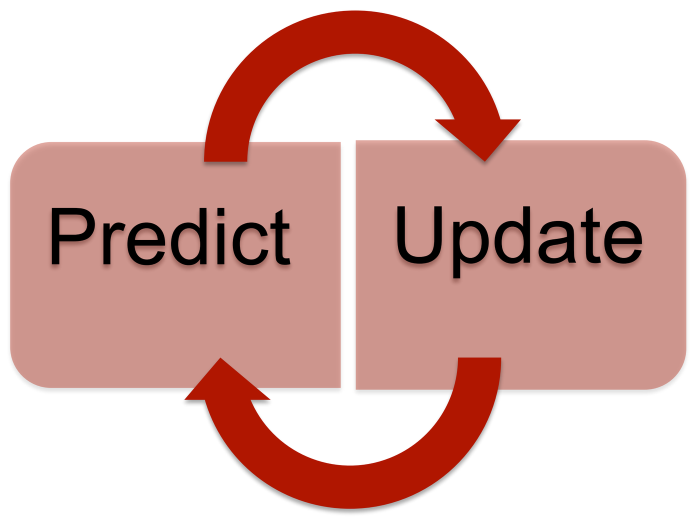
$$\vartheta_i(k+1) = \vartheta_i(k) + T_s\dot{\vartheta}_i(k) + \tfrac{1}{2}T_s^2(\ddot{\vartheta}_i(k) + \nu_k)$$
$$\dot{\vartheta}_i(k+1) = \dot{\vartheta}_i(k) + T_s(\ddot{\vartheta}_i(k) + \nu_k)$$
$$\ddot{\vartheta}_i(k+1) = \ddot{\vartheta}_i(k) + \nu_k$$

$$A_i = \begin{bmatrix} 1 & T_s & \frac{T_s^2}{2} \\ 0 & 1 & T_s \\ 0 & 0 & 1 \end{bmatrix} \quad Q_i = \begin{bmatrix} \frac{T_s^2}{2} \\ T_s \\ 1 \end{bmatrix} \begin{bmatrix} \frac{T_s^2}{2} & T_s & 1 \end{bmatrix}$$

Measurements Model

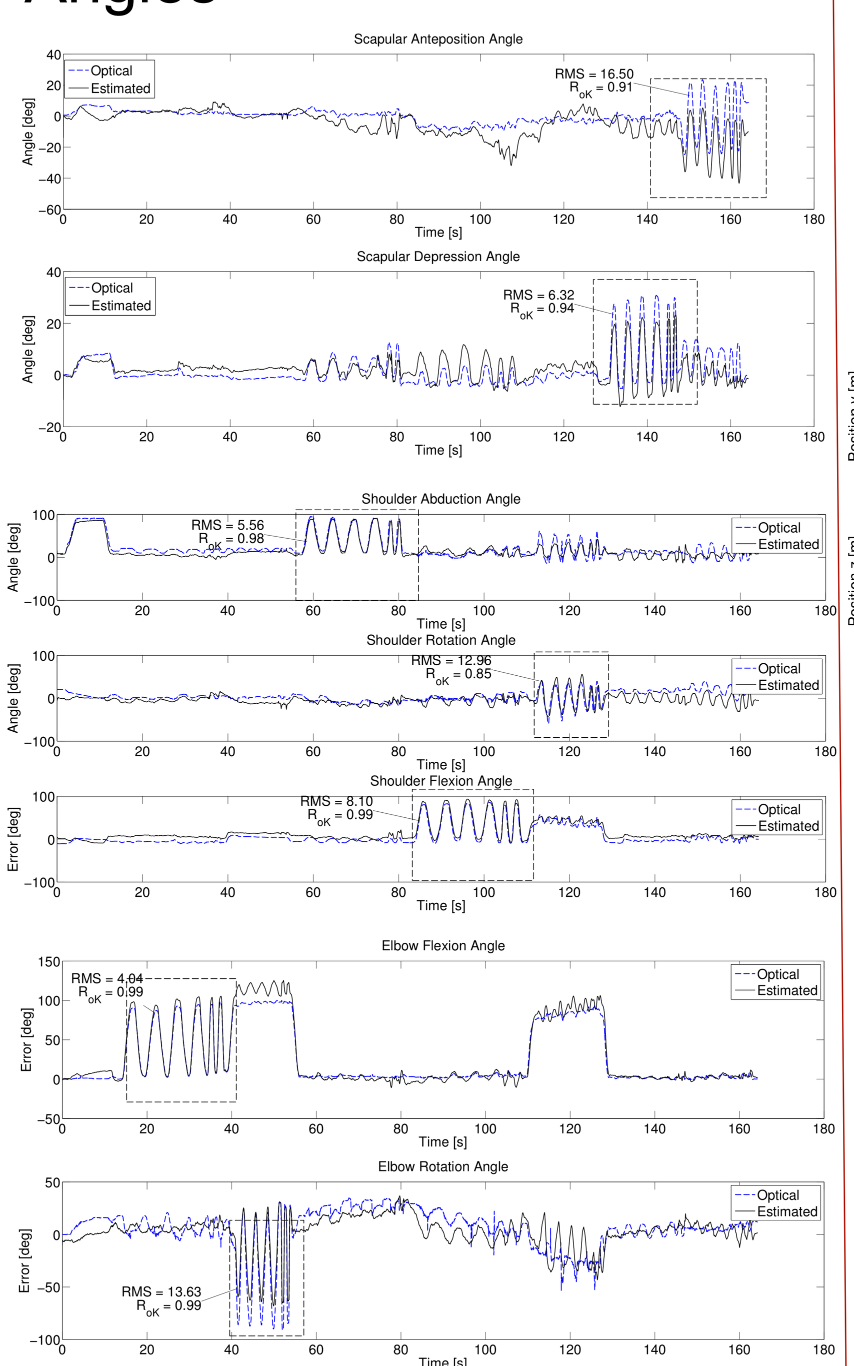
$$\omega_s^s = R_p^s(\omega_p^p + \dot{\vartheta}_{p+1}z_0)$$
$$\ddot{x}_s^s = R_p^s\ddot{x}_p^p + S(\dot{\omega}_s^s)r_{p,s}^s + S(\omega_s^s)^2 r_{p,s}^s + R_0^s g^0$$
$$m_s^s = R_0^s m^0$$

UKF



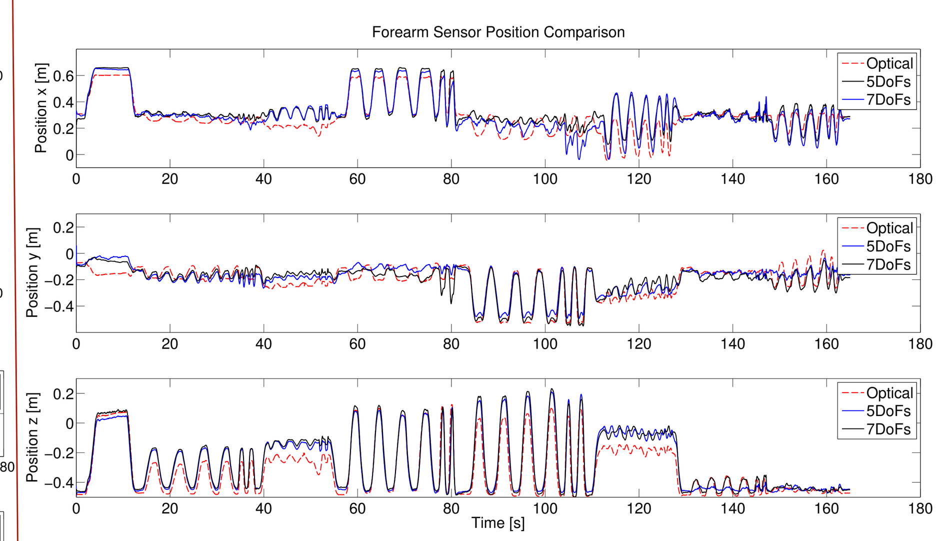
Results

Angles

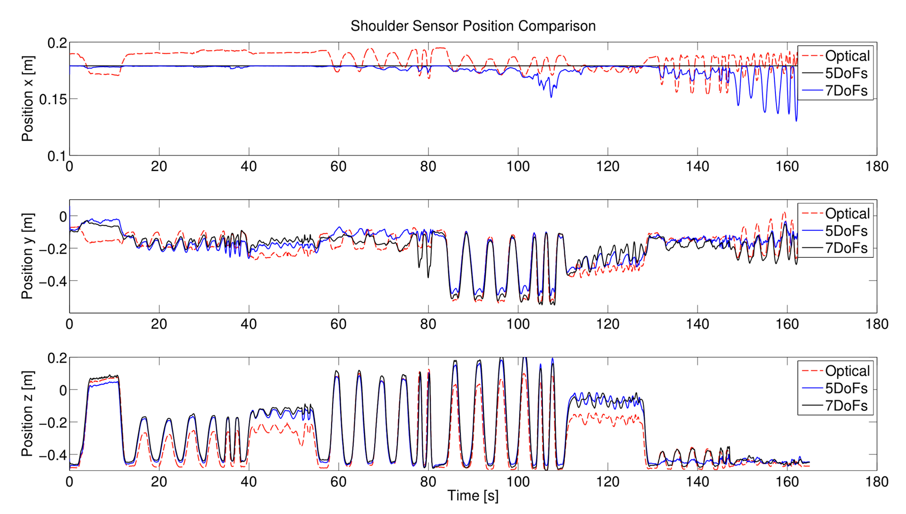


Positions

End-Effector Position



Shoulder Position



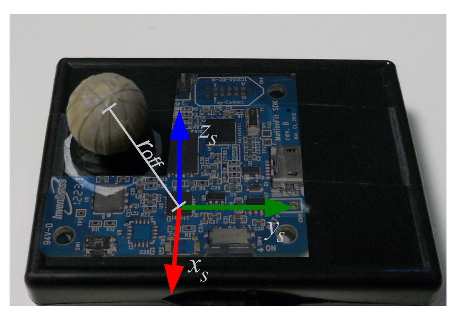
Experimental Setup

Validation

- joint angles estimation and landmarks position estimation VS optical motion capture system (Vicon MX2.0)
- joint angles estimation and landmarks position estimation VS equivalent 5 DoFs

Sensors

Three 9-axis Invensense (Invensense, Borregas Ave Sunny- vale, CA, USA) MPU9150 IMUs



Conclusions

- The comparison against models cited allowed to state that our 7 DoFs joint angle estimation is slightly better than the state of the art.
- Position estimation is better as well
- This model allows to track clavicle motion with sufficient precision, being a good starting point to tackle the problem of modeling shoulder motion
- We are now focusing on:
  - calibration procedures
  - EMG integration

Results

Angles

Variable	$E_{\vartheta_i,5}$	$E_{\vartheta_i,7}$	$C_{\vartheta_i,5}$	$C_{\vartheta_i,7}$
ϑ_1	-	6.19	-	0.65
ϑ_2	-	3.43	-	0.74
ϑ_3	7.03	8.19	0.95	0.94
ϑ_4	6.03	10.68	0.87	0.63
ϑ_5	4.95	8.79	0.99	0.97
ϑ_6	9.93	5.00	0.98	0.99
ϑ_7	11.29	9.61	0.85	0.85
Average	7.85	7.41	0.93	0.82

Positions

Variable	$E_{P_i,5}$	$E_{P_i,7}$	$C_{P_i,5}$	$C_{P_i,7}$
Shoulder	36.9	34.1	0.97	0.98
IMU arm	76.8	66.5	0.99	0.99
Elbow	70.6	65.5	0.98	0.98
IMU forearm	106.6	103.6	0.98	0.98
Average	72.7	67.4	0.98	0.98

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