Coordinate frame description of DLR's kinematic hand model

Georg Stillfried (georg.stillfried@dlr.de)

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Abstract

This document contains the description of the kinematic hand model that is provided by the German Aerospace Center (DLR) for the Hand Corpus database. The axis locations are given in the form of transformation matrices. The method for deriving this hand model is described in [1]. These matrices describe the relative position and orientation of the bone and joint coordinate frames.

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1 Abbreviations

Fingers:

1	thumb	2	index finger	3	middle finger
4	ring finger	5	little finger		

Bones:

MC	metacarpal bone	PP	phalanx proximalis
PM	phalanx media	PD	phalanx distalis

Joints:

CMC	carpometacarpal joint	IMC	intermetacarpal joint
MCP	metacarpophalangeal joint	PIP	proximal interphalangeal joint
DIP	distal interphalangeal joint		

2 Coordinate frames

Each bone and each joint and has a coordinate frame, see Fig. 1. The coordinate frames of the bones are set according to the ISB recommendations [2]. The coordinate frames of the joints are set so that the z-Axis is the axis of rotation.

For each coordinate frame, a transformation matrix to the parent frame is given in the form ${}^{\text{parent}}T_{\text{child}}$, see Eq. (1)-(43). The top left 3×3 matrix of each transformation matrix describes the orientation of each frame with respect to the parent frame, whereas the top right 3×1 column vector describes the position with respect to the parent frame, in millimetre (mm) unit.

The relative transformation matrices can be combined by multiplication. For example, the transformation of the index finger distal phalanx in world coordinates is given by:

$$^{\text{world}}T_{\text{DP2}} = {}^{\text{world}}T_{\text{MC2}}\,{}^{\text{MC2}}T_{\text{MCP2a}}\,{}^{\text{MCP2a}}T_{\text{MCP2b}}\,{}^{\text{MCP2b}}T_{\text{PP2}}\,{}^{\text{PP2}}T_{\text{PIP2}}\,{}^{\text{PIP2}}T_{\text{PM2}}\,{}^{\text{PM2}}T_{\text{DIP2}}\,{}^{\text{DIP2}}T_{\text{PD2}}.$$

The matrices of Eq. (1)-(43) are also given in higher precision in the MATLAB variable `T.mat`. `T.mat` contains the cell array of matrices `T`. The appropriate matrix can be accessed in MATLAB by suffixing the equation number in curly braces, e.g. `T{2}` for $^{\text{MC2}}T_{\text{CMC1a}}$.

$$^{\text{world}}T_{\text{MC2}} = \begin{pmatrix} 1.000 & 0.000 & 0.000 & 0.00 \\ 0.000 & 1.000 & 0.000 & 0.00 \\ 0.000 & 0.000 & 1.000 & 0.00 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{1}$$

$$^{\text{MC2}}T_{\text{CMC1a}} = \begin{pmatrix} 0.900 & -0.411 & -0.147 & 19.50 \\ -0.411 & -0.684 & -0.602 & 26.95 \\ 0.147 & 0.602 & -0.785 & 4.43 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\text{CMC1a}}, \tag{2}$$

$$^{\text{CMC1a}}T_{\text{CMC1b}} = \begin{pmatrix} 0.694 & -0.535 & -0.482 & -17.37 \\ 0.488 & -0.143 & 0.861 & -9.71 \\ -0.530 & -0.833 & 0.162 & 0.00 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\text{CMC1b}}, \tag{3}$$

$$^{\text{CMC1b}}T_{\text{MC1}} = \begin{pmatrix} -0.242 & -0.613 & 0.752 & 33.55 \\ -0.818 & 0.546 & 0.182 & -12.48 \\ -0.522 & -0.572 & -0.633 & 12.16 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{4}$$

$$^{\text{MC1}}T_{\text{MCP1a}} = \begin{pmatrix} 0.984 & -0.179 & -0.008 & 1.37 \\ -0.179 & -0.980 & -0.088 & -17.80 \\ 0.008 & 0.088 & -0.996 & -0.85 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\text{MCP1a}}, \tag{5}$$

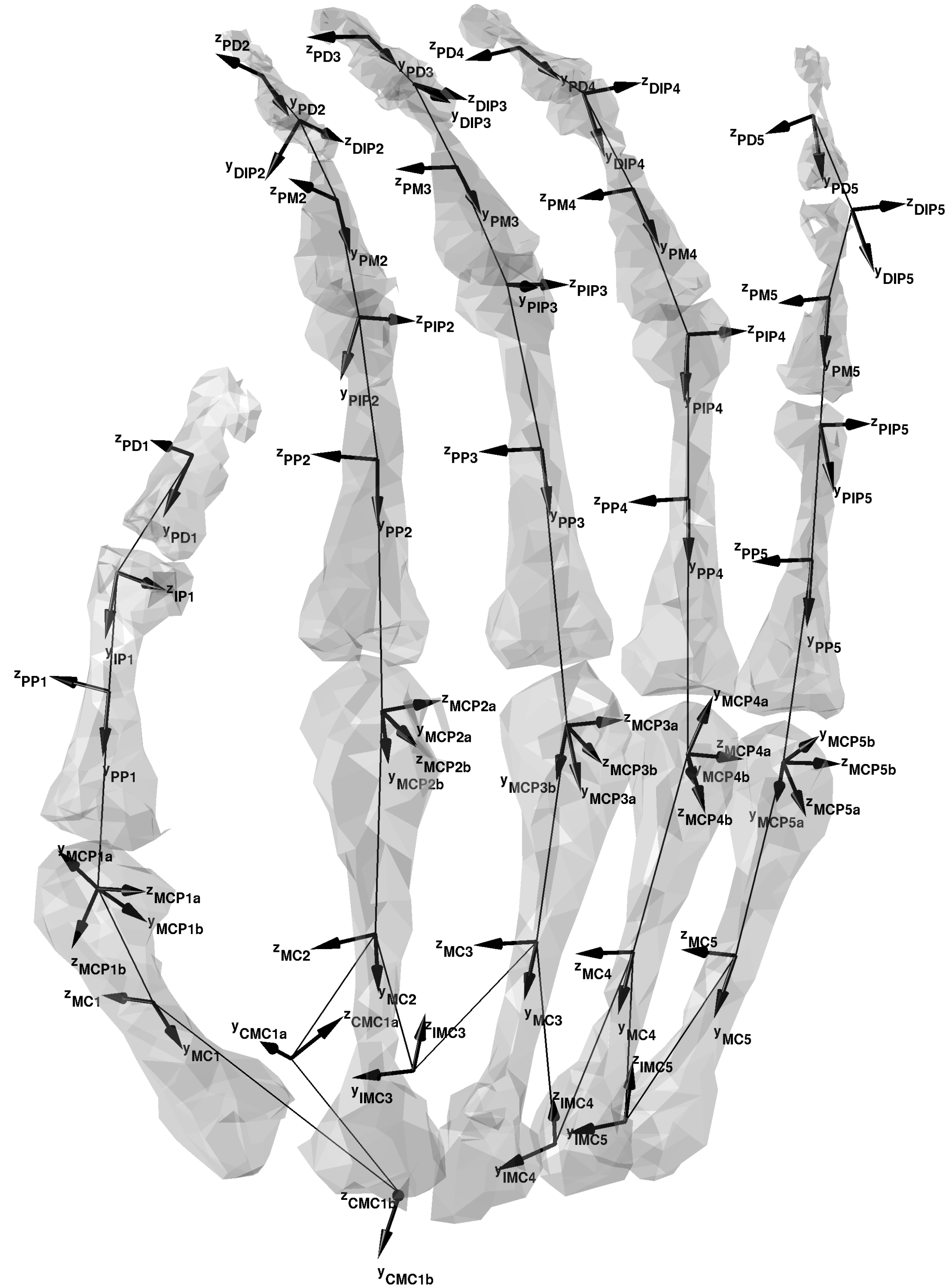

Figure 1: Coordinate frames for bones and joints. It should be noted that there is a discrepancy between the joint coordinate systems (JCS) in this model and the recommendations for JCS by the International Society for Biomechanics (ISB) [2]. In this model, the extension is a positive rotation around the z-axis of the flexion/extension JCS, while in the ISB recommendations, flexion is positive and takes places around the e_1-axis of a common JCS. In this model, radial

$$
{}^{\mathrm{MCP1a}}T_{\mathrm{MCP1b}} = \begin{pmatrix} 0.011 & 0.070 & -0.998 & 0.00 \\ -0.163 & -0.984 & -0.071 & 0.00 \\ -0.987 & 0.163 & 0.000 & -0.00 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP1b}}, \tag{6}
$$

$$
{}^{\mathrm{MCP1b}}T_{\mathrm{PP1}} = \begin{pmatrix} 0.389 & 0.333 & 0.859 & -8.82 \\ 0.655 & 0.556 & -0.512 & -14.72 \\ -0.648 & 0.762 & -0.003 & -17.33 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{7}
$$

$$
{}^{\mathrm{PP1}}T_{\mathrm{IP1}} = \begin{pmatrix} -0.952 & -0.142 & -0.270 & 1.91 \\ -0.142 & 0.990 & -0.020 & -13.64 \\ 0.270 & 0.020 & -0.963 & 1.36 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{IP1}}, \tag{8}
$$

$$
{}^{\mathrm{IP1}}T_{\mathrm{PD1}} = \begin{pmatrix} -0.918 & 0.368 & -0.146 & -7.67 \\ 0.365 & 0.930 & 0.046 & -14.11 \\ 0.152 & -0.011 & -0.988 & 1.28 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{9}
$$

$$
{}^{\mathrm{MC2}}T_{\mathrm{MCP2a}} = \begin{pmatrix} -0.021 & -0.985 & 0.173 & 1.13 \\ -0.985 & 0.050 & 0.167 & -28.94 \\ -0.173 & -0.167 & -0.971 & -2.59 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP2a}}, \tag{10}
$$

$$
{}^{\mathrm{MCP2a}}T_{\mathrm{MCP2b}} = \begin{pmatrix} -0.270 & -0.962 & -0.040 & 0.00 \\ -0.011 & -0.038 & 0.999 & -0.00 \\ -0.963 & 0.270 & 0.000 & 0.00 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP2b}}, \tag{11}
$$

$$
{}^{\mathrm{MCP2b}}T_{\mathrm{PP2}} = \begin{pmatrix} 0.034 & 0.457 & 0.889 & -12.67 \\ 0.773 & 0.552 & -0.313 & -17.85 \\ -0.634 & 0.697 & -0.335 & -20.01 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{12}
$$

$$
{}^{\mathrm{PP2}}T_{\mathrm{PIP2}} = \begin{pmatrix} -0.732 & 0.601 & 0.320 & 2.67 \\ 0.601 & 0.792 & -0.111 & -17.70 \\ -0.320 & 0.111 & -0.941 & 1.49 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{PIP2}},
$$

(13)

$$ {}^{\mathrm{PIP2}}T_{\mathrm{PM2}} = \begin{pmatrix} -0.509 & 0.861 & 0.020 & -14.30 \\ 0.821 & 0.492 & -0.290 & -8.64 \\ -0.259 & -0.131 & -0.957 & 2.85 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{14} $$

$$ {}^{\mathrm{PM2}}T_{\mathrm{DIP2}} = \begin{pmatrix} -0.537 & 0.841 & 0.059 & 1.15 \\ 0.841 & 0.539 & -0.032 & -11.68 \\ -0.059 & 0.032 & -0.998 & 1.72 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{DIP2}}, \tag{15} $$

$$ {}^{\mathrm{DIP2}}T_{\mathrm{PD2}} = \begin{pmatrix} -0.268 & 0.962 & -0.051 & -10.85 \\ 0.963 & 0.269 & 0.013 & -1.66 \\ 0.026 & -0.046 & -0.999 & 1.81 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{16} $$

$$ {}^{\mathrm{MC2}}T_{\mathrm{IMC3}} = \begin{pmatrix} 0.991 & -0.103 & -0.085 & 0.27 \\ -0.103 & -0.189 & -0.976 & 19.68 \\ 0.085 & 0.976 & -0.198 & -3.82 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{IMC3}}, \tag{17} $$

$$ {}^{\mathrm{IMC3}}T_{\mathrm{MC3}} = \begin{pmatrix} 0.997 & -0.025 & 0.074 & -4.95 \\ -0.073 & 0.016 & 0.997 & -9.68 \\ -0.026 & -1.000 & 0.014 & 19.97 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{18} $$

$$ {}^{\mathrm{MC3}}T_{\mathrm{MCP3a}} = \begin{pmatrix} -0.685 & -0.706 & 0.180 & 2.49 \\ -0.706 & 0.705 & 0.075 & -27.89 \\ -0.180 & -0.075 & -0.981 & 0.57 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP3a}}, \tag{19} $$

$$ {}^{\mathrm{MCP3a}}T_{\mathrm{MCP3b}} = \begin{pmatrix} -0.097 & -0.734 & 0.672 & -0.00 \\ 0.088 & 0.667 & 0.740 & -0.00 \\ -0.991 & 0.132 & 0.000 & 0.00 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP3b}}, \tag{20} $$

$$ {}^{\mathrm{MCP3b}}T_{\mathrm{PP3}} = \begin{pmatrix} -0.079 & 0.165 & 0.983 & -5.86 \\ 0.730 & 0.682 & -0.056 & -22.63 \\ -0.679 & 0.713 & -0.174 & -22.17 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{21} $$

$$
{}^{\mathrm{PP3}}T_{\mathrm{PIP3}} = \begin{pmatrix} -0.242 & -0.969 & 0.052 & 2.98 \\ -0.969 & 0.244 & 0.040 & -19.84 \\ -0.052 & -0.040 & -0.998 & 0.41 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{PIP3}}, \tag{22}
$$

$$
{}^{\mathrm{PIP3}}T_{\mathrm{PM3}} = \begin{pmatrix} -0.746 & -0.665 & -0.036 & 12.80 \\ -0.665 & 0.746 & 0.035 & -14.65 \\ 0.004 & 0.050 & -0.999 & 0.44 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{23}
$$

$$
{}^{\mathrm{PM3}}T_{\mathrm{DIP3}} = \begin{pmatrix} -0.831 & -0.473 & 0.291 & 0.12 \\ -0.473 & 0.878 & 0.075 & -13.69 \\ -0.291 & -0.075 & -0.954 & -0.13 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{DIP3}}, \tag{24}
$$

$$
{}^{\mathrm{DIP3}}T_{\mathrm{PD3}} = \begin{pmatrix} -0.946 & -0.180 & -0.269 & 2.32 \\ -0.163 & 0.983 & -0.084 & -12.60 \\ 0.279 & -0.036 & -0.959 & 0.72 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{25}
$$

$$
{}^{\mathrm{MC3}}T_{\mathrm{IMC4}} = \begin{pmatrix} 0.971 & -0.140 & -0.192 & 0.60 \\ -0.140 & 0.315 & -0.939 & 28.41 \\ 0.192 & 0.939 & 0.287 & -8.01 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{IMC4}}, \tag{26}
$$

$$
{}^{\mathrm{IMC4}}T_{\mathrm{MC4}} = \begin{pmatrix} 0.969 & -0.235 & 0.081 & 3.04 \\ 0.025 & 0.418 & 0.908 & -12.87 \\ -0.247 & -0.878 & 0.411 & 22.43 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{27}
$$

$$
{}^{\mathrm{MC4}}T_{\mathrm{MCP4a}} = \begin{pmatrix} 0.993 & -0.114 & 0.006 & 0.73 \\ -0.114 & -0.987 & 0.111 & -24.81 \\ -0.006 & -0.111 & -0.994 & -1.46 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP4a}}, \tag{28}
$$

$$
{}^{\mathrm{MCP4a}}T_{\mathrm{MCP4b}} = \begin{pmatrix} 0.287 & 0.354 & -0.890 & 0.00 \\ -0.561 & -0.692 & -0.455 & 0.00 \\ -0.777 & 0.630 & -0.000 & 0.00 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP4b}},
$$

$$(29)$$

$$ {}^{\mathrm{MCP4b}}T_{\mathrm{PP4}} = \begin{pmatrix} 0.434 & 0.249 & 0.866 & -7.69 \\ 0.696 & 0.517 & -0.498 & -15.09 \\ -0.572 & 0.819 & 0.051 & -24.05 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{30}$$

$$ {}^{\mathrm{PP4}}T_{\mathrm{PIP4}} = \begin{pmatrix} -0.991 & 0.132 & 0.015 & 0.14 \\ 0.132 & 0.991 & -0.001 & -18.86 \\ -0.015 & 0.001 & -1.000 & -0.29 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{PIP4}}, \tag{31}$$

$$ {}^{\mathrm{PIP4}}T_{\mathrm{PM4}} = \begin{pmatrix} -0.745 & 0.662 & 0.080 & -11.96 \\ 0.667 & 0.741 & 0.075 & -14.71 \\ -0.010 & 0.110 & -0.994 & -1.25 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{32}$$

$$ {}^{\mathrm{PM4}}T_{\mathrm{DIP4}} = \begin{pmatrix} -0.982 & 0.185 & -0.038 & 0.20 \\ 0.185 & 0.983 & 0.004 & -13.04 \\ 0.038 & -0.004 & -0.999 & 0.54 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{DIP4}}, \tag{33}$$

$$ {}^{\mathrm{DIP4}}T_{\mathrm{PD4}} = \begin{pmatrix} -0.758 & 0.650 & 0.053 & -8.80 \\ 0.652 & 0.757 & 0.047 & -8.94 \\ -0.009 & 0.070 & -0.997 & -0.69 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{34}$$

$$ {}^{\mathrm{MC4}}T_{\mathrm{IMC5}} = \begin{pmatrix} 0.999 & -0.028 & -0.033 & 1.33 \\ -0.028 & 0.150 & -0.988 & 22.39 \\ 0.033 & 0.988 & 0.149 & -5.55 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{IMC5}}, \tag{35}$$

$$ {}^{\mathrm{IMC5}}T_{\mathrm{MC5}} = \begin{pmatrix} 0.998 & -0.054 & 0.014 & 2.59 \\ 0.002 & 0.282 & 0.959 & -14.33 \\ -0.056 & -0.958 & 0.282 & 17.65 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{36}$$

$$ {}^{\mathrm{MC5}}T_{\mathrm{MCP5a}} = \begin{pmatrix} 0.211 & 0.418 & -0.884 & 1.75 \\ 0.418 & 0.779 & 0.468 & -23.47 \\ 0.884 & -0.468 & -0.010 & 1.20 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP5a}},$$

(37)

$$ {}^{\mathrm{MCP5a}}T_{\mathrm{MCP5b}} = \begin{pmatrix} -0.102 & -0.367 & -0.924 & -0.00 \\ -0.248 & -0.891 & 0.381 & -0.00 \\ -0.963 & 0.268 & 0.000 & -0.00 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{MCP5b}}, \tag{38} $$

$$ {}^{\mathrm{MCP5b}}T_{\mathrm{PP5}} = \begin{pmatrix} 0.550 & -0.835 & -0.022 & 19.15 \\ -0.833 & -0.548 & -0.075 & 14.51 \\ 0.051 & 0.060 & -0.997 & -0.59 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{39} $$

$$ {}^{\mathrm{PP5}}T_{\mathrm{PIP5}} = \begin{pmatrix} -0.879 & -0.424 & 0.219 & 1.01 \\ -0.424 & 0.904 & 0.050 & -15.50 \\ -0.219 & -0.050 & -0.974 & -0.50 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{PIP5}}, \tag{40} $$

$$ {}^{\mathrm{PIP5}}T_{\mathrm{PM5}} = \begin{pmatrix} -0.893 & -0.449 & -0.029 & 6.34 \\ -0.450 & 0.891 & 0.054 & -13.48 \\ 0.002 & 0.061 & -0.998 & -0.82 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \tag{41} $$

$$ {}^{\mathrm{PM5}}T_{\mathrm{DIP5}} = \begin{pmatrix} -0.800 & -0.596 & -0.071 & 0.18 \\ -0.596 & 0.802 & -0.023 & -10.06 \\ 0.071 & 0.023 & -0.997 & -2.68 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos(q) & -\sin(q) & 0 & 0 \\ \sin(q) & \cos(q) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \text{ with } q = q_{\mathrm{DIP5}}, \tag{42} $$

$$ {}^{\mathrm{DIP5}}T_{\mathrm{PD5}} = \begin{pmatrix} -0.871 & -0.492 & 0.015 & 4.89 \\ -0.479 & 0.854 & 0.203 & -10.17 \\ -0.113 & 0.170 & -0.979 & -4.87 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{43} $$

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