Daily life requirements of robotic systems that mimic human lower limb movement

Anforderungen an robotische Systeme zur Nachbildung von menschlichen Beinbewegungen des Alltags

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Abstract

The analysis of biomechanics in different daily activities is essential to help understanding the diverse and complicated processes involved in human locomotion and supporting the evaluation of joint replacement or prostheses development. This article summarized the biomechanical joint requirements for different activities of daily life and also discussed the mechanical principle, which can be applied to decrease power and energy requirements. As a result of a systematic literature research, 13 daily movements were identified, which are walking, jogging, running, stairs ascent and descent, pick up loads, climbing uphill and downhill, sit to stand, squat jump, recovery and cycling. The kinematic and kinetic parameters consist of power, torque, angular velocity, angular acceleration and range of motion. After the comparison of the research data with hypotheses, it was shown that the largest kinematic and kinetic parameters were required during recovery, running and squat jump. In addition, the comparison of different mechanical principle showed that, springs and dampers are the most commonly used structures so far, also because they can easily be integrated into passive prostheses. We hope that our work can help to implement other mechanical principles in prostheses, in order to have them more comfortable, natural and affordable.

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1 Abbreviations

Abbreviations

A	Ascent
D	Descent
W	Walking
J	Jogging
RN	Running
SQ	Squat
ST	Stoop
UH	Uphill
DH	Downhill
STS	Sit to stand
C	Cycling
R	Recovery
ROM	Range of motion
SJ	Squat Jump
P-F	Plantar-Flexion
DF	Dorsiflexion
S+P	springs in (Series and Parallel)
CPEA	Clutched Parallel Elastic Actuatorv
VSA	Variable Stiffness Actuators

2 Introduction

Although daily activities are relative normal for healthy people, some of them are overly demanding for those, whose joint functions are reduced. For example, subjects affected by muscle or joint diseases as well as subjects with joint or limb replacements. Despite advancements in medicine and the emphasis on disease prevention, limb loss continues to be prevalent in our society. In 2005, 1.6 million people were estimated to be living with limb loss in the United States. By 2050, the rate is expected to double to 3.6 million [19]. The sharp increase in the number of disabled people has led to an increasing in the demand for prosthetic devices. Therefore, analysis of joint biomechanics in daily activities can help to understand the complicated joint movements and further also can be used in the design of prostheses.

Recently, most studies focused on the analysis of the change of joint parameters during stair and slope walking [14][17]. Some studies also investigated the biomechanical requirements of joints between different lifting techniques [9]. In addition, some researchers have noticed that, sit to stand movement is a complex dynamic task that requires regulation of lower limb muscles to drive the human body while rising from a stable seated position to a relatively unstable upright stance [11]. However, no comprehensive analysis is available that compares the joint biomechanics between all daily activities.

The purpose of this study is to analyze joint kinematics and kinetics in healthy subjects during daily activities including walking, running, climbing stairs, jumping and etc, which are believed to be the most commonly performed activities during daily living [17]. Furthermore, this paper also discussed the mechanical principle of design a prosthetic leg, which can be applied to decrease power and energy requirements.

3 Lower extremity joints

3.1 Hypothesis

- **Hip**

Because for squat jump range of motion of hip joint in a short time is larger (velocity is higher) and it needs large torque for take-off, the maximum power for hip joint is predicted to occur during squat jump, and this peak power is predicted to be in stance phase because angle variation during stance phase is larger than swing phase (nearly 0 ° in swing phase) and torque in stance phase is also obviously larger than swing, in swing phase the requirement for torque is nearly 0 Nm.

It is hypothesized that squat requires the greatest torque, because the hip joint must provide the torque for movement of upper body and lifting extra weight (15 kg).For pick up loads there are only stance phase in the cycle for lower limbs.

Hip joint during running has the possibility to require the maximum velocity and acceleration, because cycle duration for running is relatively short, while the angle variation is also high. Maximum of velocity and acceleration can be in swing phase, because the hip joint flexes and extends rapidly for higher forward speed.

- **Knee**

Usually during stance phase the knee moment and power are high, while the angular acceleration and velocity are low. During swing phase it is opposite. Based on this acknowledgement, it is hypothesized that the maximum torque occurred in midstance of running, while the maximum power would be produced during the late stance of squat jump. In stance of running the single leg takes on the full weight of body. Therefore, a very large extending torque would be required. As already known that power is the product of torque and angular acceleration. The motion with maximum power must have both large torque and large acceleration. According to the prediction, in squat jump the knee angle range is large and the gait cycle is short. Furthermore, the torque during the late stance of squat jump must work against the body weight. Thus, it is predicted that, the peak power of knee is in the squat jump.

Based on the prediction of knee joint kinematics (angular velocity and angular acceleration), the peak angular velocity and angular acceleration are the largest during the swing phase of recovery. The reason is that recovery is a special movement, during which the body must lift the low limb as quickly as possible in order to take a big step forward to maintain balance. Therefore, the knee angle must change rapidly.

- **Ankle**

The kinetics (Power and Torque) for ankle are hypothesized as following. The maximum power can occur due to large amount of extending torque, very high angular velocity, or both of them. So the maximum Power is hypothesized to occur at the stance phase at running activity. That can be due to the high required velocity to produce the next step. On the other hand the maximum extending torque would be considered to be at the end phase of stance for squat move during picking up loads. That is because, while lifting the weight a rotational force is required to move the weight against the gravitational force also to lift body parts to the start position.

For the ankle kinematics The maximum kinematics are expected to occur at the end of swing phase at running activity due to higher change of the ankle's angle under the speed of the motion.

3.2 Methods

In this research activities such as Stairs assent and descent, pickup loads, walking, climbing uphill and downhill, and other daily activities have been studied for lower extremities, including activities at different elevations (climbing uphill and downhill) and at different speeds(1.6 m/s, 2.6 m/s and 4 m/s) to examine the full range of human motion.The table shown below (Table 3.1) illustrates the different activities studied, the amount of participants for each activity, their characteristics, and the literature of which each activity was discussed in.

Tabelle 3.1: Table Participants

Motions	**Participant**				
	Literature	Age [Years]	Height [m]	Weight [Kg]	Number
1-Ascent	[16]	28.8 ± 2.9	1.79 ± 0.05	82.2 ± 8.5	10
2-Descent	[16]	28.8 ± 2.9	1.79 ± 0.05	82.2 ± 8.5	10
3-Pick up loads Squat	[9]	23.5 ± 0.76	1.721 ± .06.3	55.6 - 74.5	26
4-Pick up loads Stoop	[9]	23.5 ± 0.76	1.721 ± .06.3	55.6 - 74.5	26
5-Walking [1.6 m\s]	[6]	25.4	1.73	70.9	21
6-Jogging [2.6 m\s]	[6]	25.4	1.73	70.9	21
7-Running [4 m\s]	[6]	23.7	1.8	77.5	21
8-Climbing Uphill	[10]	24 ± 3	1.78 ± 0.08	73.36 ± 8.6	9
9-Climbing Downhill	[10]	24 ± 3	1.78 ± 0.08	73.36 ± 8.6	9
10-STS	[11]	28.1 ± 6.3	1.735 ± 0.067	67.3 ± 8.5	5
11-Jumping	[12]	21.6 ± 2.73	1.8641 ± 0.0513	78.16 ± 8.15	6
12-Cycling	[3]	25.3 ± 5.7	1.8 ± 0.06	71.3 ± 5	6
13-Recovery	[13]	19 -23 [Young]	1.76 ± 0.07 [Young]	71.3 ± 14 [Young]	10 [Young]
		65 - 83 [Old]	1.71 ± 0.06 [Old]	77 ± 14 [Old]	10 [Old]

The collected data was then normalized to represent the *gait cycle* as a percentile of the time duration of each motion. Furthermore, the gait cycle is divided into stance and swing phases and are provided as normalized intervals, as shown in (Table 3.2).

Tabelle 3.2: Time phases

Motion		Gait cycle		
		Stance [%]	Swing [%]	Time [s]
1- Ascent	Min [24°]	0-60	60-100	1.4
	Norm [30°]	0-60	60-100	1.41
	Max [42°]	0-60	60-100	1.47
2-Descent	Min [24°]	0-60	60-100	1.2
	Norm [30°]	0-60	60-100	1.19
	Max [42°]	0-60	60-100	1.22
Level walking	/	0-60	60-100	1.11
3-Pick up loads Squat	/	0-100	/	2
4-Pick up loads Stoop	/	0-100	/	2
5-Walking [1.6 m/s]	/	0-60	60-100	0.978
6-Jogging [2.6 m/s]	/	0-38	38-100	0.7506
7-Running [4 m/s]	/	0-34	34-100	0.7034
8-Climbing Uphill	slope 39%	0-62.5	62.5-100	1.95
	slope 15%	0-61	61-100	1.23
Level walking	slope 0%	0-61.7	61.7-100	1.2
9-Climbing Downhill	slope -15%	0-62.4	62.4-100	1.17
	slope-39%	0-62.7	62.7-100	1.18
10-STS	/	0-100	/	3
11-Jumping	/	0-42	58-100	1
12-Cycling	/	0-100	/	1
13-Recovery	/	/	0-100	0.5

For our study a set of parameters for each activity is required. These parameters include: Power, Torque, Velocity, Acceleration and Range of motion (ROM). Some of these parameters were provided by the literature and are marked by (o), while the remaining parameters were obtained and calculated using the numerical software tool Matlab and are marked by (x), as shown in (Table 3.3).

Tabelle 3.3: Calculation

Motions	Parameters				
	Power	Torque	Velocity	Acceleration	ROM
1- Ascent	o	o	x	x	o
2-Descent	o	o	x	x	o
3-Pick up loads Squat	o	o	x	x	o
4-Pick up loads Stoop	o	o	x	x	o
5-Walking [1.6 m/s]	o	o	o	o	o
6-Jogging [2.6 m/s]	o	o	o	o	o
7-Running [4 m/s]	o	o	o	o	o
8-Climbing Uphill	x	o	x	x	o
9-Climbing Downhill	x	o	x	x	o
10-STS	x	o	x	o	o
11-Jumping	o	o	x	x	o
12-Cycling	o	x	o	x	o
13-Recovery	o	o	o	x	x

Based on the statistical data of the American population aged over 20 years [5], the scales of different physiological needs were compared, namely, the 5th percentile of females 50.1 Kg, the 50th percentile of males 85.9 Kg and the 95th percentile of males 124.9 Kg. Furthermore for the weight of different percentiles were normalized to the 50th percentile of males, as shown in (Table 3.4).

Tabelle 3.4: Weight in Kilograms for males and females aged 20 and over

Gender	Women	Men	Men
Percentile [%]	5	50	95
Weight [Kg]	50.1	85.9	124.9
Ratio to 50%	0.583236	1	1.454016

In the following three sections the joints have been analyzed and going to be discussed. For the different activities, the maximum values of their parameters are remarked in red and have been listed in 3 different tables (ROM, acceleration vs velocity and power vs torque), except the ROM Tables, the red color represents the boundaries of the interval of each activity. On the other hand if the stance phase, respectively the swing phase doesn't exist ,it has been marked with (/).For simplicity and more clear presentation, only the 50th percentile have been plotted in charts and coded with three colors for the 3 different joints (Hip, Knee and Ankle) with (Red, Green, Blue) respectively. For the 95th and 5th percentile, the results can be calculated with the ration to the 50th percentile with the help of (Table 3.4).

3.3 Hip

In this section the kinematic and kinetic parameters of hip joint for 13 kinds of daily motions will be described and discussed. In this paper we define that hip angle is the angle between trunk and thigh on sagittal plane, it is 180° when trunk and thigh are in one line (standing position).

3.3.1 Results

Figures below (Fig. 3.1-Fig. 3.2) show the change of the normalized kinematic and kinetic data for daily motions in gait cycle.

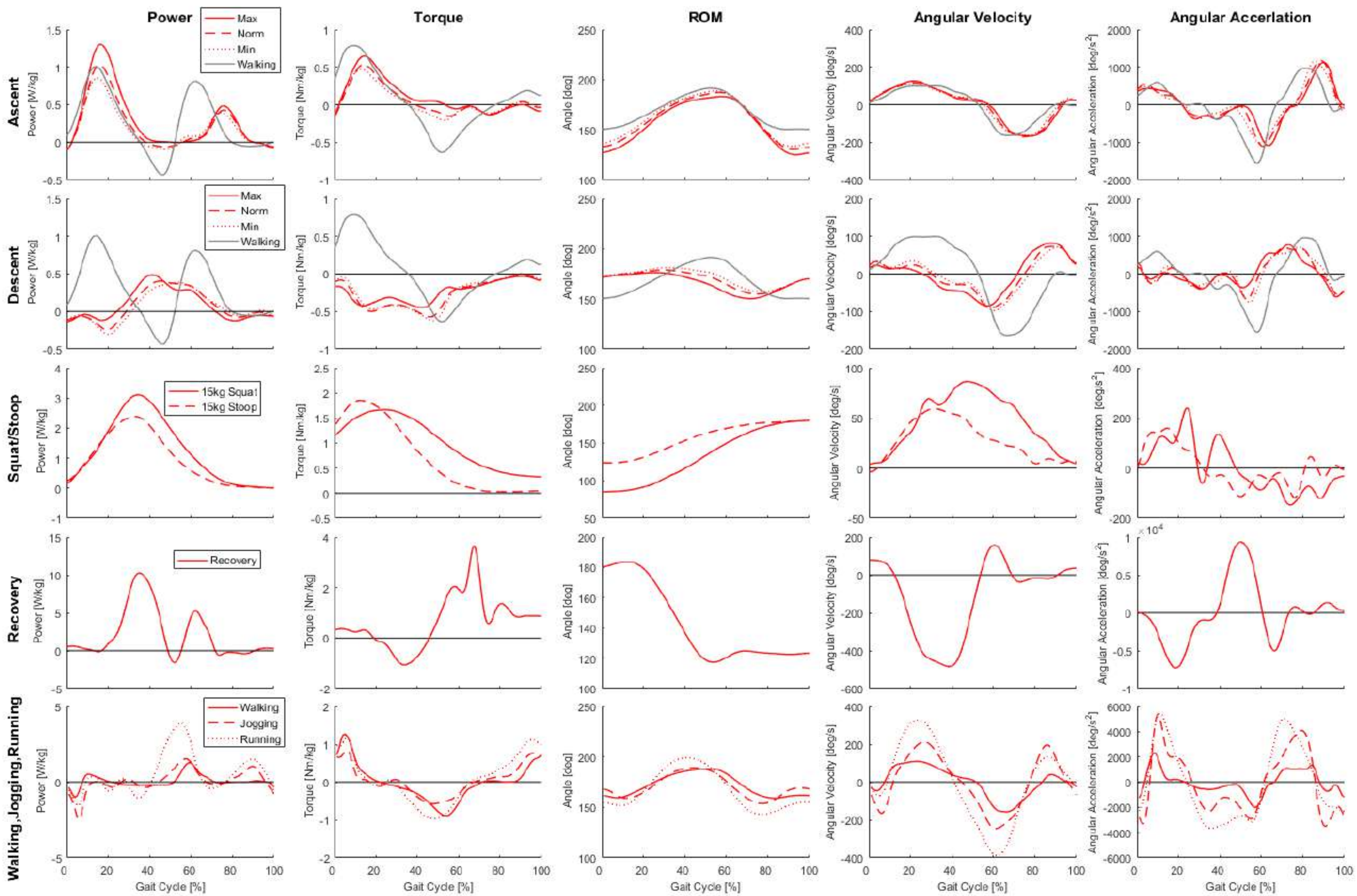

Abbildung 3.1: Hip joint movement for Ascent, Descent, Pick up load, Recovery and Walking

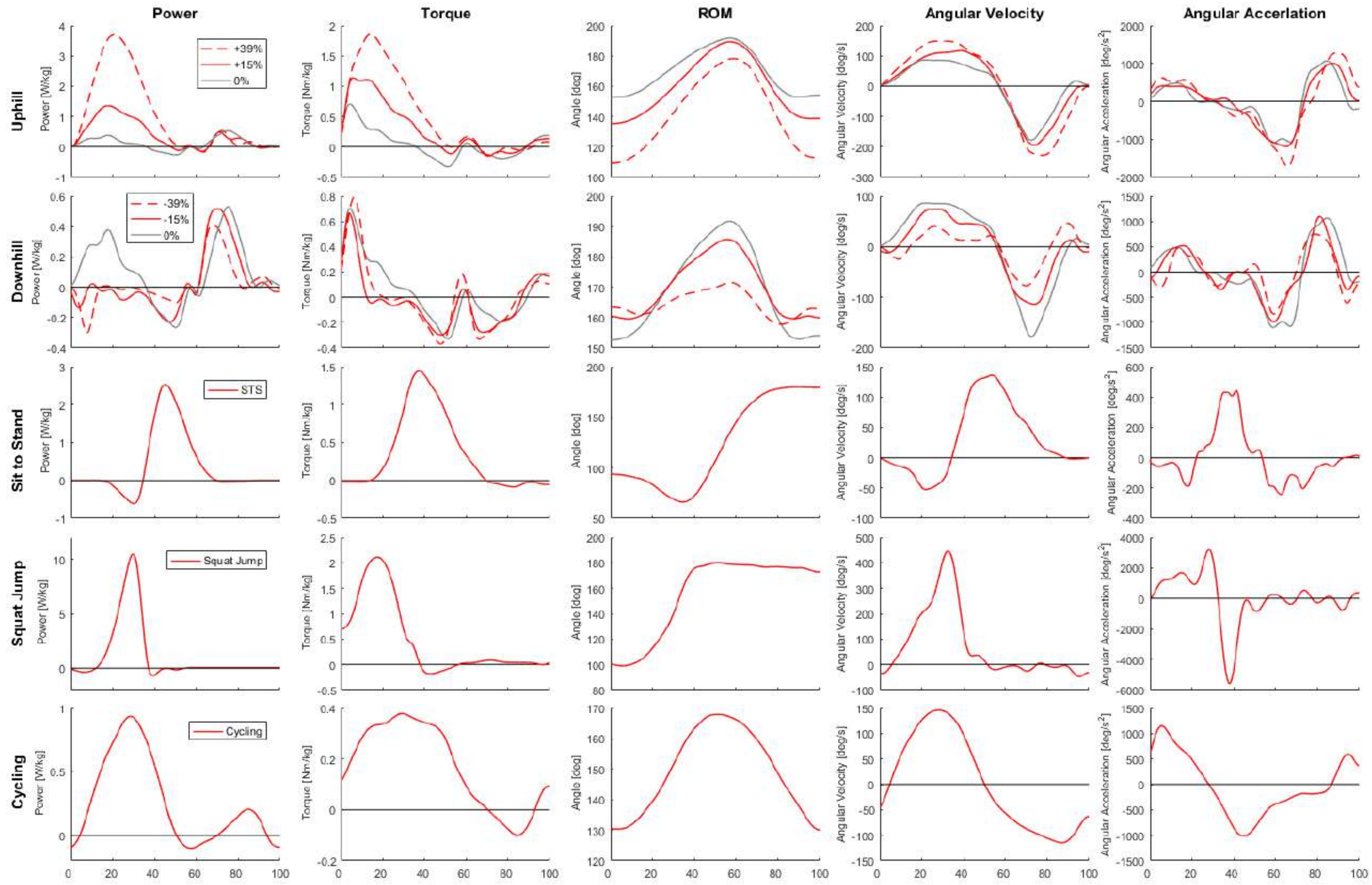

Abbildung 3.2: Hip joint movement for Climbing, Sit to stand, Jump and Cycling

(Table 3.5) and figure(Fig. 3.3) show the ROM of hip joint for 13 kinds of daily motions. Angular velocity and acceleration in total, stance, and swing phase are shown in (Table 3.6) and figures below (Fig. 3.4-Fig. 3.6). Positive angular velocity represents extension phase and negative represents flexion phase.

Tabelle 3.5: Hip ROM

Motions			ROM [°]	
			Stance	**Swing**
1- Ascent	**Min**	**Max**	188.65	186.45
		Min	136.51	133.51
	Norm	**Max**	187.21	186.20
		Min	132.99	130.47
	Max	**Max**	183.14	182.87
		Min	127.06	125.02
2-Descent	**Min**	**Max**	181.26	170.12
		Min	169.16	170.12
	Norm	**Max**	178.91	170.07
		Min	164.45	154.97
	Max	**Max**	176.27	170.06
		Min	156.24	150.24
	Level walking	**Max**	191.51	187.32
		Min	150.48	150.34
3-Pick up loads	**Squat 15Kg**	**Max**	180.00	/
		Min	85.03	
	Stoop 15Kg	**Max**	180.00	
		Min	123.69	

4-Walking	Walking	Max	188.18	183.37
		Min	159.40	159.08
	Jogging	Max	187.37	188.99
		Min	159.05	153.71
	Running	Max	194.62	199.14
		Min	151.71	142.92
5-Climbing	Uphill 15%	Max	189.28	181.28
		Min	135.37	138.69
	Uphill 39%	Max	178.20	172.22
		Min	109.09	113.06
	0 Deg level	Max	191.75	184.36
		Min	152.55	152.83
	Donwhill -15%	Max	185.71	178.47
		Min	159.54	159.63
	Donwhill -39%	Max	171.51	166.99
		Min	160.99	157.76
6-STS	Sit to Stand	Max	180.00	/
		Min	66.11	
7-Jumping	Squat Jump(SJ)	Max	176.96	180.00
		Min	98.99	172.86
8-Cycling		Max	167.94	/
		Min	130.03	
9-Recovery		Max	/	183.74
		Min		117.36

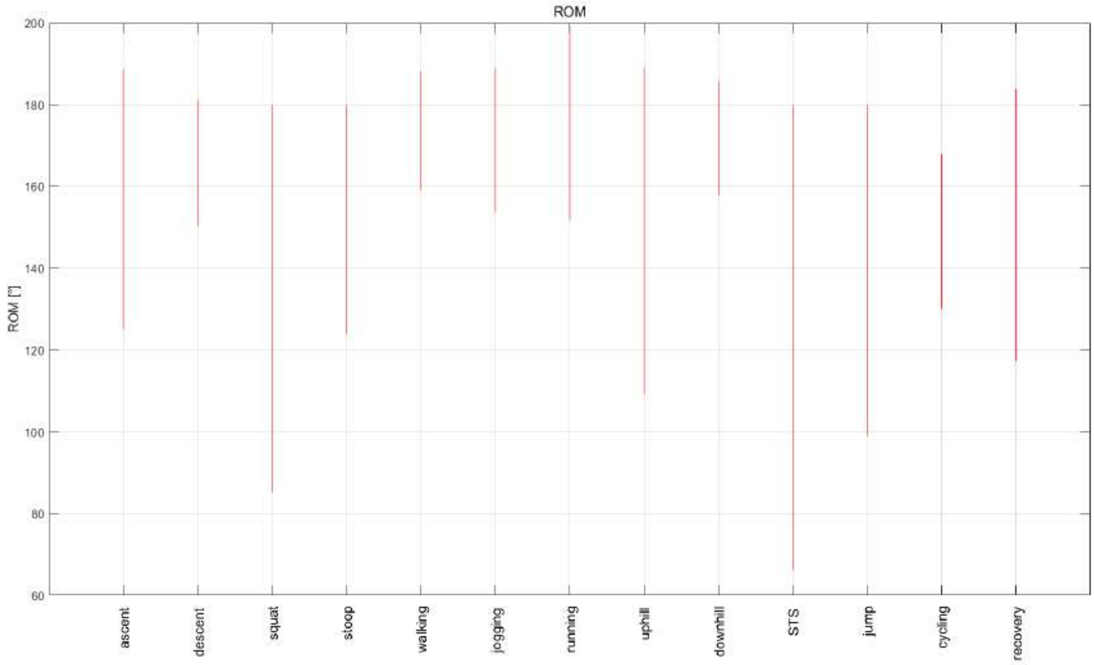

Abbildung 3.3: Hip ROM

From (Table 3.5) and (Fig. 3.3) it is easy to find that ROM of hip joint for STS-activity is the largest (113.89 °,from 66.11 °to 180 °), secondly is for SQ-activity (94.97 °,from 85.03 °to 180 °), then for SJ-activity (81.01 °,from 98.99 °to 180 °).ROM for DH-activity is the smallest (27.95 °, from 157.76 ° to 185.71 °).In addition, the maximum hip angle for RN-activity is the largest, which is 199.14 °, while the minimum hip angle for STS-activity is the smallest, which is only 66.11 °.

Tabelle 3.6: Hip Velocity vs Acceleration

Motions			Velocity[°/s]		Acceleration[°/s²]	
			Stance	Swing	Stance	Swing
1- Ascent	Min	Pos	111.55	33.47	485.04	1156.60
		Neg	-67.50	-163.56	-1009.90	-999.36
	Norm	Pos	116.99	28.34	542.78	1172.70
		Neg	-46.41	-170.35	-1091.50	-1105.40
	Max	Pos	126.17	24.39	429.07	1128.70
		Neg	-22.54	-166.39	-858.41	-1085.30
2-Descent	Min	Pos	34.24	71.62	245.09	714.46
		Neg	-97.59	-97.75	-749.83	-589.16
	Norm	Pos	32.79	72.82	307.39	693.15
		Neg	-90.38	-88.89	-665.91	-546.16
	Max	Pos	22.94	82.35	330.56	780.60
		Neg	-84.91	-79.01	-390.31	-612.16
	Level walking	Pos	99.75	5.45	598.59	964.65
		Neg	-114.06	-163.63	-1553.60	-1406.70
3-Pick up loads	Squat 15Kg	Pos	86.56	/	240.24	/
		Neg	/		-147.00	
	Stoop 15Kg	Pos	59.27		159.53	
		Neg	/		-117.36	
4-Walking	Walking	Pos	109.36	38.37	2305.80	1359.10
		Neg	-142.42	-157.28	-2017.30	-1401.10
	Jogging	Pos	209.59	191.97	5413.30	4095.60
		Neg	-166.55	-244.56	-3329.40	-3529.80
	Running	Pos	326.87	155.30	5458.20	5038.30
		Neg	-72.99	-385.99	-3597.60	-3679.80

5-Climbing	Uphill 15%	Pos	117.23	/	408.58	1002.70
		Neg	-133.76	-194.71	-1191.80	-1155.30
	Uphill 39%	Pos	148.88	/	623.24	1282.40
		Neg	-142.49	-227.89	-1726.50	-1697.50
	0 Deg level	Pos	86.50	-177.92	479.48	1068.30
		Neg	-122.17	/	-1098.90	-1077.30
	Donwhill -15%	Pos	74.81	13.11	517.73	1097.80
		Neg	-100.43	-113.59	-981.11	-349.63
	Donwhill -39%	Pos	40.44	46.74	476.62	747.52
		Neg	-69.81	-77.56	-832.84	-614.31
6-STS	Sit to Stand	Pos	136.28	/	443.43	/
		Neg	-52.52		-243.04	
7-Jumping	Squat Jump(SJ)	Pos	446.47	53.70	3204.90	544.74
		Neg	-34.86	-47.13	-5580.20	-2540.40
8-Cycling		Pos	-114.94	/	1150.40	/
		Neg	145.99		-1018.80	
9-Recovery		Pos	/	155.55	/	9364.00
		Neg		-483.72		-7265.70

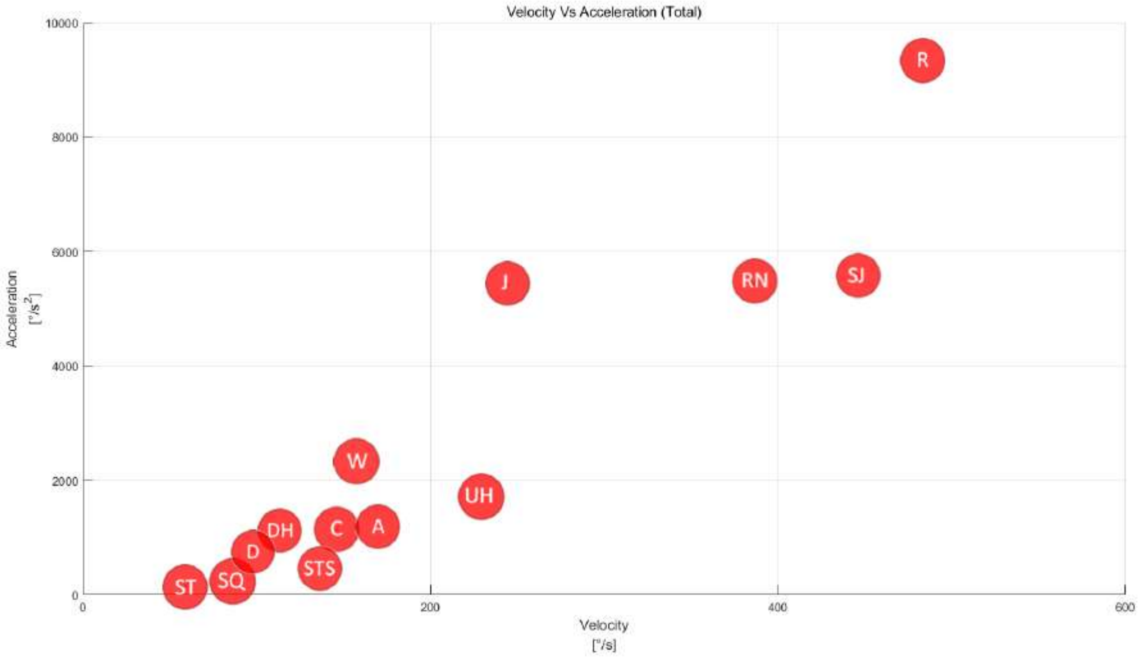

Abbildung 3.4: Hip Velocity vs Acceleration in Total phase

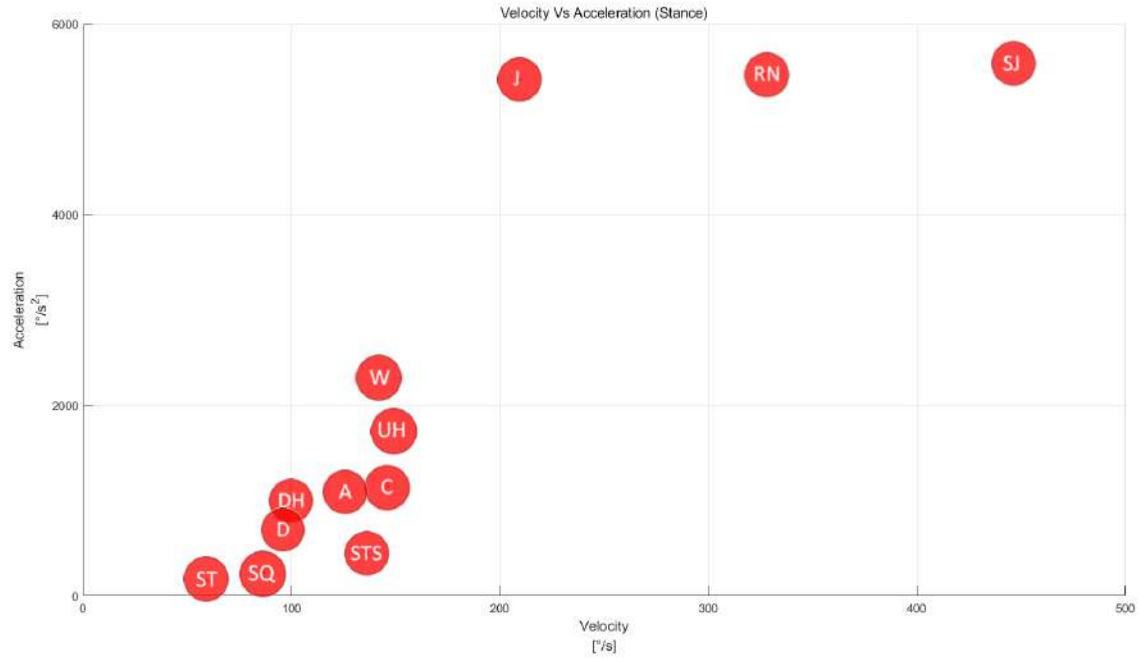

Abbildung 3.5: Hip Velocity vs Acceleration in Stance phase

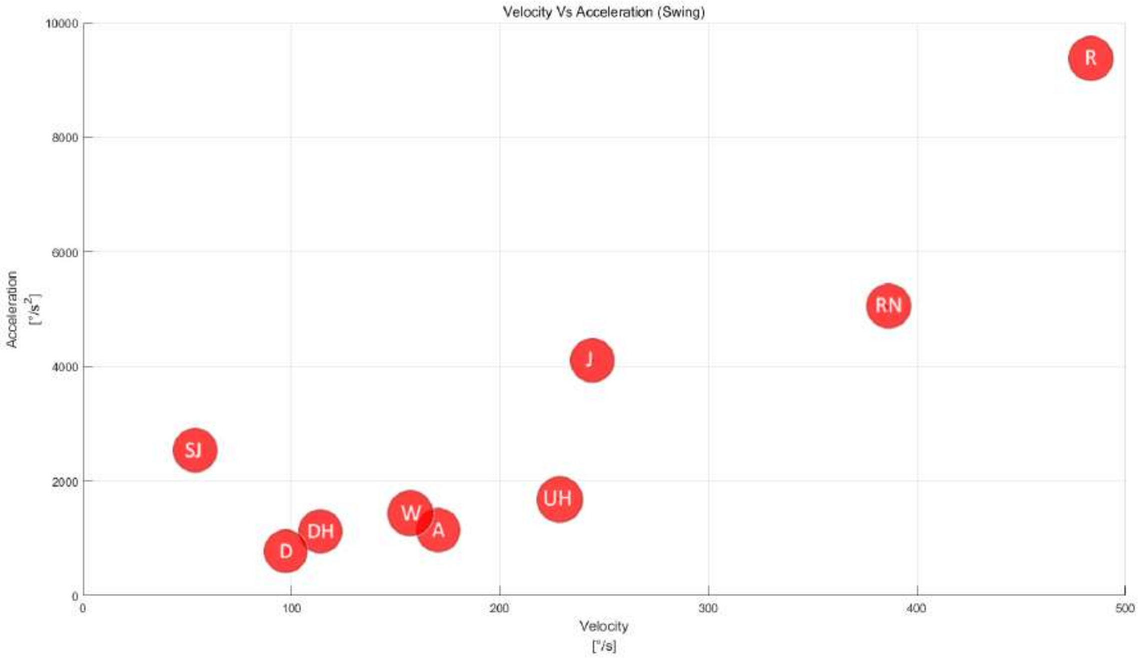

Abbildung 3.6: Hip Velocity vs Acceleration in Swing phase

In 13 kinds of motion R-activity requires the maximum angular velocity and angular acceleration, which are 483.72 °/s and 9364 °/s². Requirement of angular acceleration during stance phase for SJ-activity, J-activity and RN-activity are nearly the same, about 5500 °/s². For SJ-activity requirement of angular velocity is also high, which is 446.47 °/s during stance phase. It is worth mentioning that except SJ-activity the angular velocity for other 12 kinds of motion during swing phase are higher than stance. Conversely angular acceleration for most motions during stance phase is higher than swing, except A-activity, D-activity and DH-activity.

(Table 3.7) shows the peak power and torque of hip joint, and figures below (Fig. 3.7-Fig. 3.9) show the relationship between peak power and torque for different daily motions in total stance, and swing phase. Torque is positive when the muscle extends, it is negative when muscle flexes.

Tabelle 3.7: Hip Power vs Torque

Motions			Power [W/Kg]		Torque [Nm/Kg]	
			Stance	Swing	Stance	Swing
1- Ascent	Min	Pos	0.86	0.40	0.47	0.03
		Neg	-0.10	-0.06	-0.21	-0.12
	Norm	Pos	1.03	0.43	0.53	0.04
		Neg	-0.10	-0.06	-0.15	-0.12
	Max	Pos	1.30	0.48	0.65	0.00
		Neg	-0.11	-0.08	-0.14	-0.14
2-Descent	Min	Pos	0.39	0.33	/	/
		Neg	-0.30	-0.06	-0.62	-0.18
	Norm	Pos	0.40	0.34	/	/
		Neg	-0.25	-0.08	-0.57	-0.19
	Max	Pos	0.49	0.28	/	/
		Neg	-0.13	-0.12	-0.45	-0.20
	Level walking	Pos	1.01	0.81	0.79	0.19
		Neg	-0.43	-0.05	-0.63	-0.41
3-Pick up loads	Squat 15Kg	Pos	3.11	/	1.67	/
		Neg	/		/	
	Stoop 15Kg	Pos	2.39		1.85	
		Neg	/		/	
4-Walking	Walking	Pos	1.28	1.26	1.27	0.73
		Neg	-1.01	-0.34	-0.89	-0.56
	Jogging	Pos	0.20	1.54	0.85	0.76
		Neg	-2.48	-0.78	-0.30	-0.57
	Running	Pos	0.37	3.91	1.19	1.12
		Neg	-1.55	-1.05	-0.35	-0.97

5-Climbing	Uphill 15%	**Pos**	1.36	0.49	1.14	0.13
		Neg	-0.15	-0.04	-0.11	-0.15
	Uphill 39%	**Pos**	3.69	0.52	1.86	0.08
		Neg	-0.17	-0.03	-0.02	-0.14
	0 Deg level	**Pos**	0.38	0.53	*0.71*	0.19
		Neg	-0.27	0.00	*-0.33*	-0.19
	Donwhill -15%	**Pos**	0.48	0.52	0.67	0.18
		Neg	-0.23	-0.03	-0.30	-0.28
	Donwhill -39%	**Pos**	0.40	0.41	0.79	0.13
		Neg	-0.30	-0.01	-0.37	-0.33
6-STS	Sit to Stand	**Pos**	2.53	/	1.44	/
		Neg	-0.61		-0.09	
7-Jumping	Squat Jump(SJ)	**Pos**	10.49	0.06	2.11	0.09
		Neg	-0.72	-0.30	-0.18	-0.18
8-Cycling		**Pos**	0.94	/	0.38	/
		Neg	-0.10		-0.10	
9-Recovery		**Pos**	/	10.27	/	3.64
		Neg		-1.59		-1.07

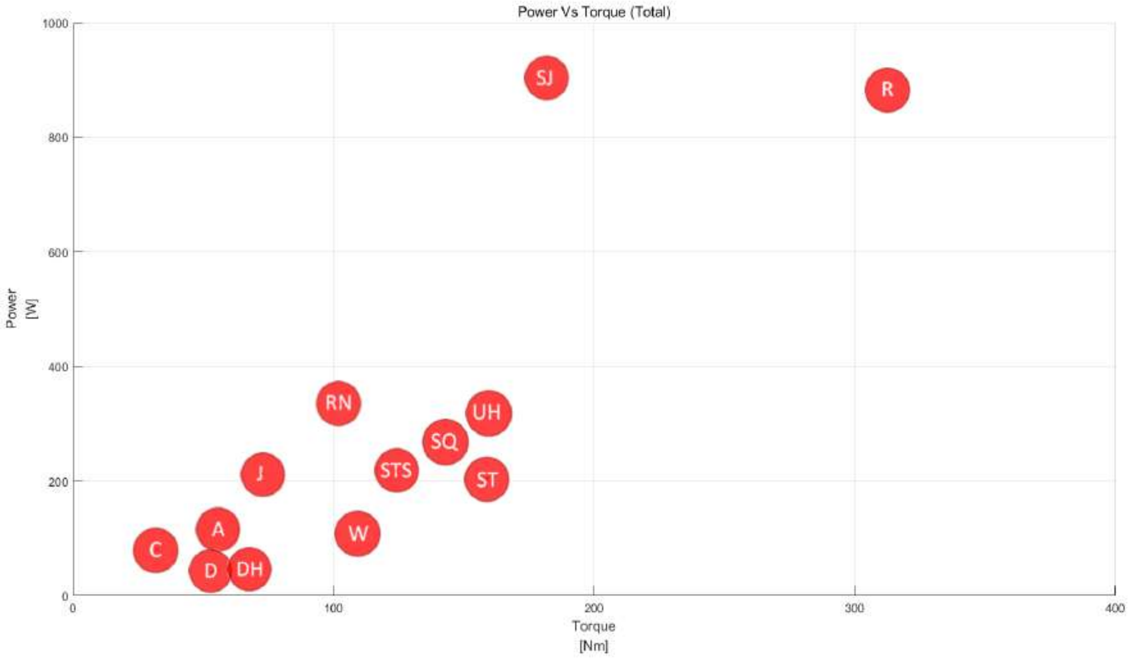

Abbildung 3.7: Hip Power vs Torque in Total phase

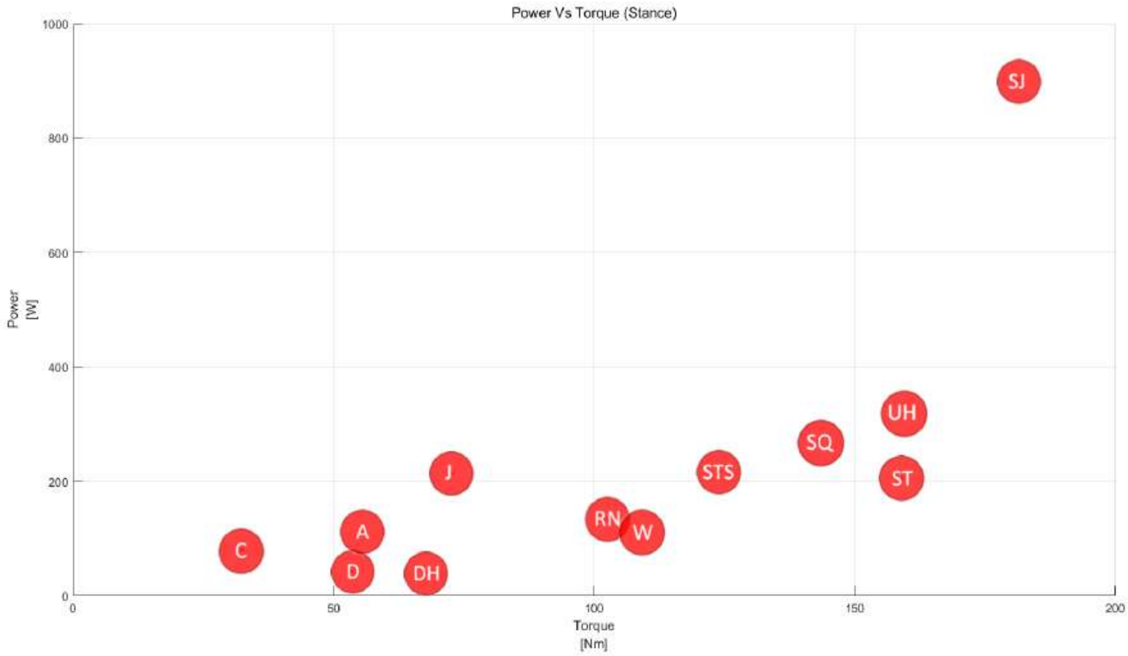

Abbildung 3.8: Hip Power vs Torque in Stance phase

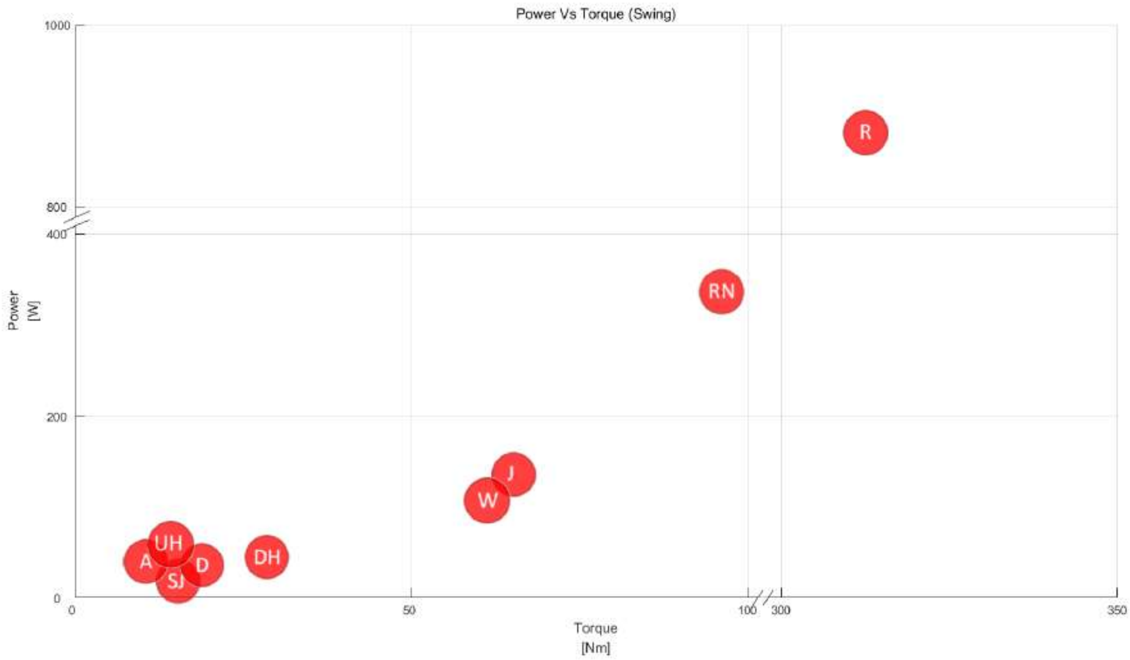

Abbildung 3.9: Hip Power vs Torque in Swing phase

For R-activity 312.54 Nm of peak torque would be required during swing phase, which is also the maximum requirement of torque in 13 kinds of motion. Peak power for R-activity is 881.83 W. SJ-activity requires a little more peak power of 901.10 W during stance phase, which is also the maximum requirement of peak power, whereas its peak torque during stance phase is only 58% of R-activity, which is 181.46 Nm. Compares with stance phase the requirement of peak power and peak torque for SJ-activity in swing phase is much lower. In addition, the most of motions require more peak power during stance phase than swing, except RN-activity, DH-activity and R-activity. Similarly, except R-activity other motions require more peak torque during stance phase than swing phase.

3.3.2 Discussion

Compares with the hypothesis for parameters of motion of hip joint, the results show a very different situation.

The maximum requirement of torque is not for SQ-activity but for R-activity. During R-activity the maximum torque for hip joint occurs when the foot contacts with the ground. Large torque was produced for hip extension in order to go forward. As the 32% body weight of the participant in the research for recovery lean forward[13], the mass center also lean forward and arm of force increase compares with normal walking and running, so that the value of torque is also larger.

R-activity also requires higher hip angular velocity and acceleration than RN-activity and it is also not the same as the hypothesis. The reason can be that for R-activity hip joint needs to quickly flex and extend in swing phase in order to keep body balance. Also the cycle time of R-activity is shorter than RN-activity and it is also the shortest in 13 kinds of daily motion, which is 0.5 s. Furthermore, the ROM of R-activity is also not so small (the fifth) and it is also larger than RN-activity, which is 66.38 °. With large ROM and short cycle time can the angular velocity and acceleration be higher.

As we known, power is the product of joint angular velocity and joint torque. It is worth mentioning that although during R-activity hip requires the maximum torque and maximum angular velocity, SJ-activity requires more power than R-activity. For R-activity, the maximum torque occurs in second half phase while the maximum angular velocity occurs in first half phase. Compares with R-activity the maximum torque and angular velocity for SJ-activity occur nearly at the same time, which results to a high power value. In addition, during SJ-activity muscle needs to provide large value of power for hip extension and then the whole body take off.

The range of motion for DH-activity in 13 kinds of motion is the smallest, only 27.96 °. During downhill trunk will remain vertical in order to keep balance, and thigh does not require a large amount of movement, so the ROM of hip joint for downhill is little. Compares with other motion requires STS-activity the largest ROM. The reason can be that when sit to stand human need to first bent down then stand up, the hip joint change from 66.11 ° to 180 °.

3.4 Knee

In this section the kinematics and kinetics of knee joint are analyzed between stance and swing phase. The knee angle is defined as the angle between thigh and shank in a sagittal plane and normalized at 180° at standing position (thigh and shank in one line).

3.4.1 Results

Firstly, the different knee parameters under the complete gait cycle are shown in the figures below (Fig. 3.10 and Fig. 3.11).

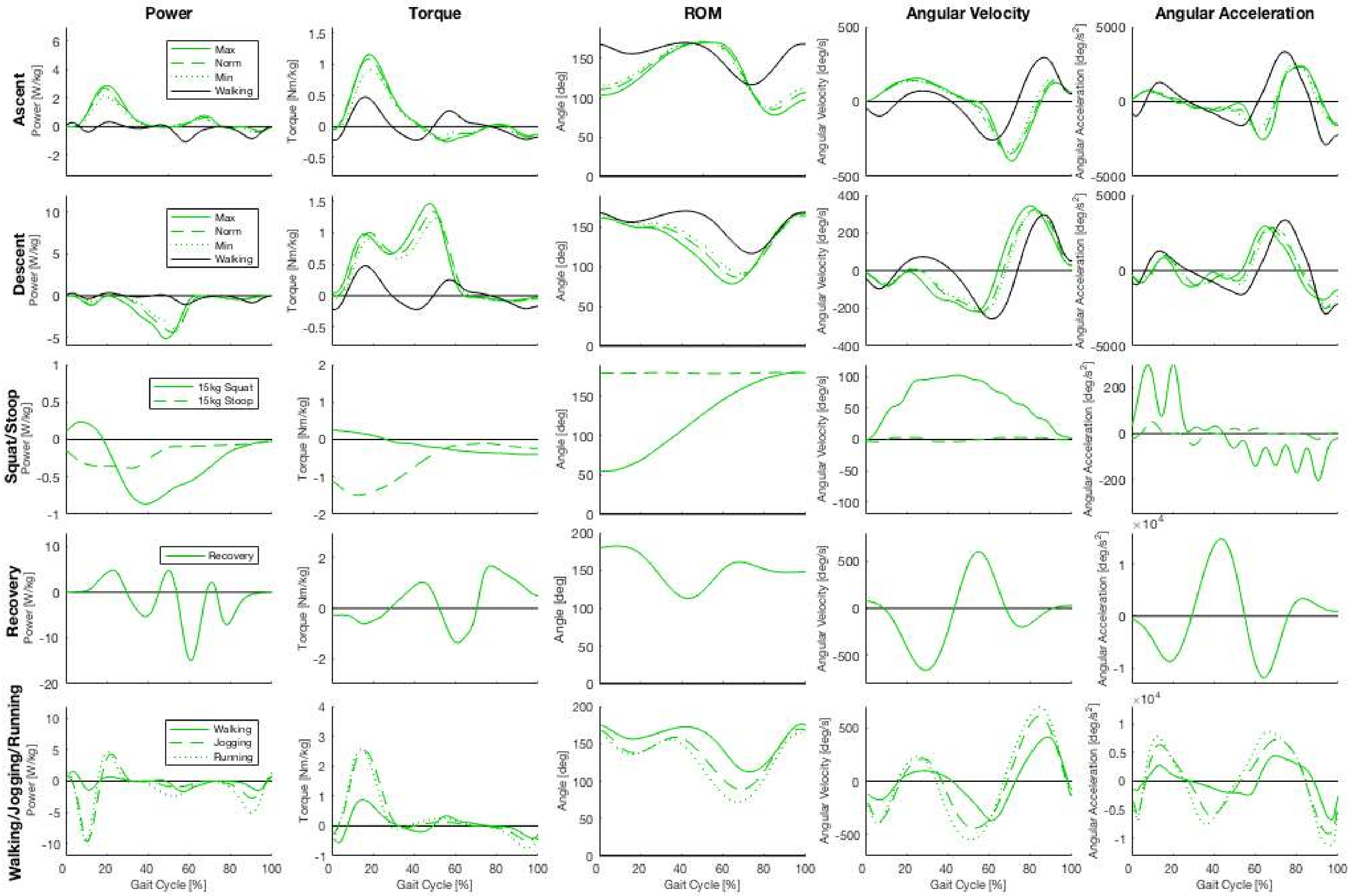

Abbildung 3.10: Knee joint movement for Ascent, Descent, Pick up load, Recovery and Walking

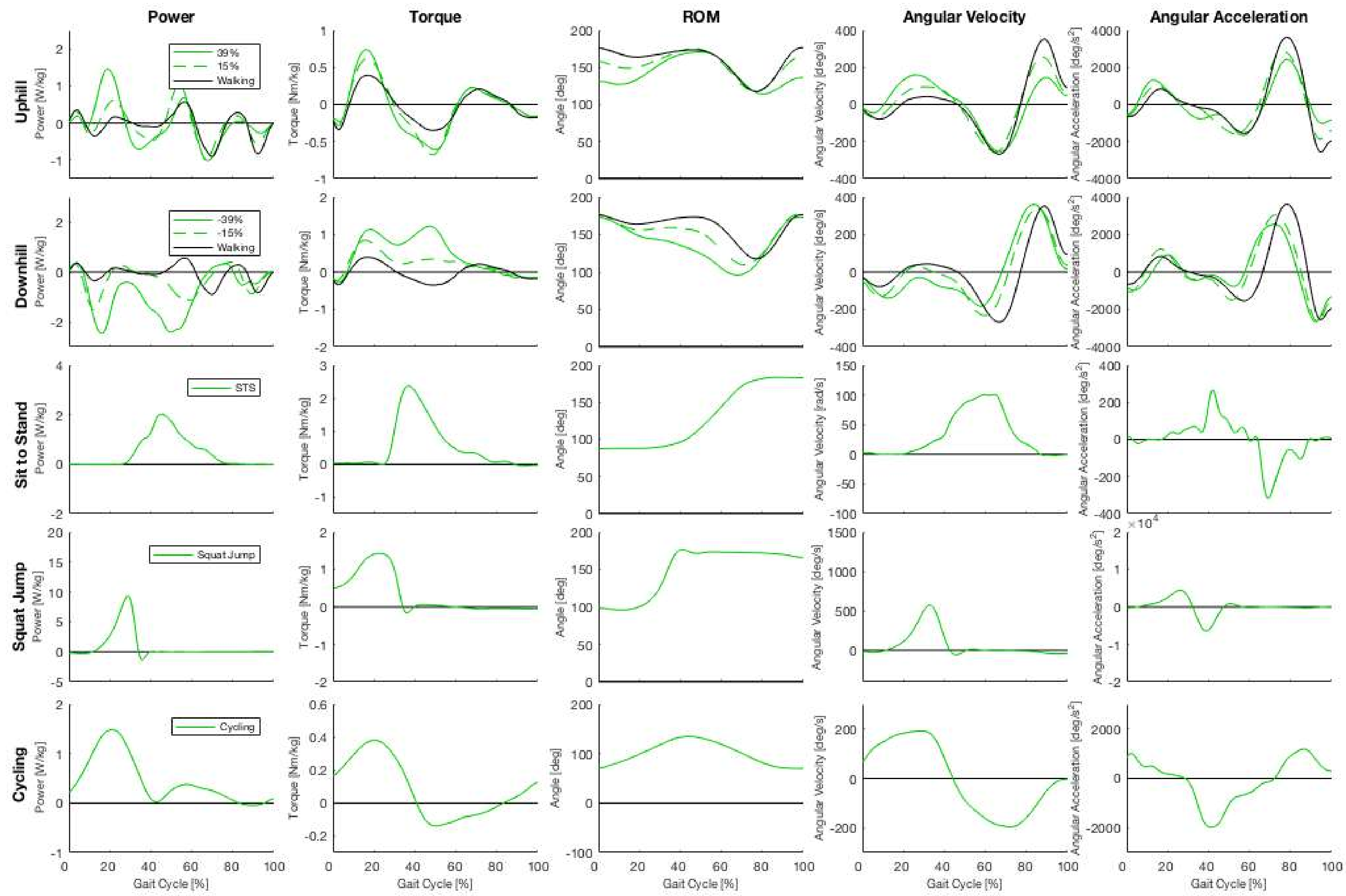

Abbildung 3.11: Knee joint movement for Climbing, Sit to stand, Jump and Cycling

The calculated maximum and minimum knee angles in stance and swing phase are shown in Table (Tab. 3.8). The total ROM of each motion are shown in chart (Fig. 3.12).

Tabelle 3.8: Knee ROM

Motions			ROM [°] Stance	ROM [°] Swing
1- Ascent	Min	Max	171.52	161.49
		Min	115.46	88.32
	Norm	Max	171.19	164.53
		Min	110.97	85.29
	Max	Max	170.03	167.75
		Min	103.35	77.84
2-Descent	Min	Max	163.73	166.36
		Min	102.69	90.93
	Norm	Max	161.19	163.55
		Min	94.91	86.63
	Max	Max	161.17	166.22
		Min	81.78	78.24
	Level walking	Max	169.98	168.3
		Min	143.75	116.55
3-Pick up loads	Squat 15Kg	Max	180	/
		Min	54.5	
	Stoop 15Kg	Max	180	
		Min	178.43	
4-Walking	Walking	Max	174.83	175.93
		Min	141.56	112.2
	Jogging	Max	167.75	169.61
		Min	137.61	89
	Running	Max	162.69	164.54
		Min	135.51	71.85

5-Climbing	Uphill 15%	Max	175.31	163.75
		Min	148.8	118.61
	Uphill 39%	Max	170.84	155.15
		Min	127.1	114.31
	0 Deg level	Max	176.59	43.16
		Min	117.79	-231.74
	Donwhill -15%	Max	177.26	177.17
		Min	124.49	109.67
	Donwhill -39%	Max	173.08	173
		Min	101.29	95.87
6-STS	Sit to Stand	Max	180	/
		Min	83.76	
7-Jumping	Squat Jump(SJ)	Max	180	180
		Min	99.41	169.59
8-Cycling		Max	134.82	/
		Min	69.88	
9-Recovery		Max	/	180
		Min		110.5

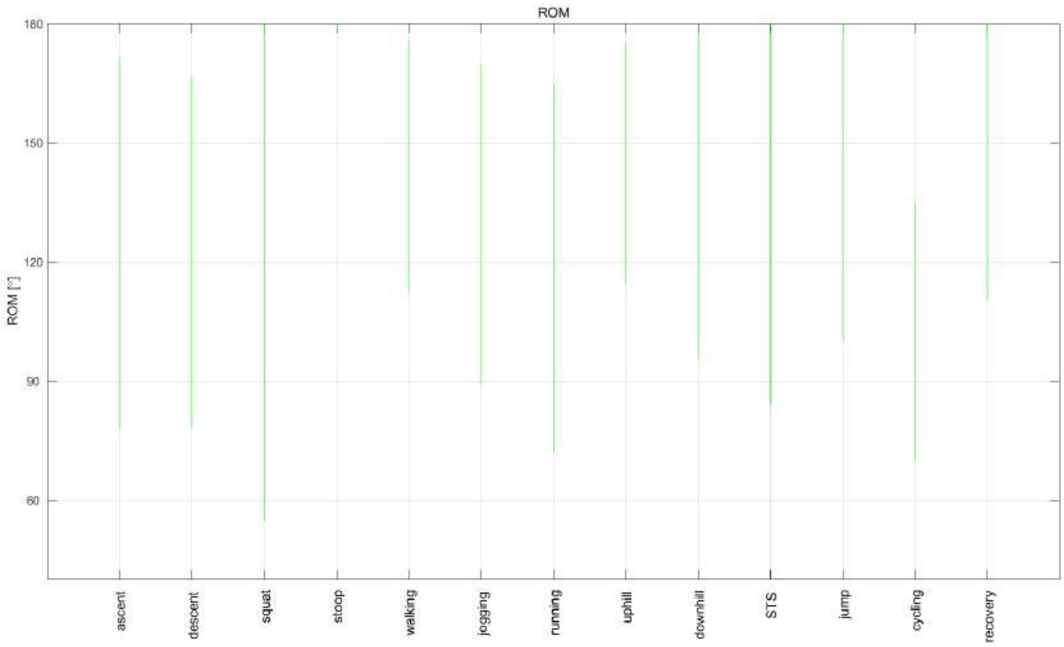

Abbildung 3.12: Knee ROM

As can be seen from the chart (Fig. 3.12), the greatest change of angle took place in SQ-activity with [55°-180°], while the minimum angle amplitude was in ST-activity with [178°-180°]. Otherwise, the joint range and maximum flexion angle of DH-activity were larger than that of UH-activity (DH [96°-177°] and UH [114°-175°]). Because during downslope walking greater knee flexion angles are required to lower the body down the slope. It is noteworthy that, during C-activity the maximum extension angle with 130° was smaller than that of other motions.

Then the angular velocity and angular acceleration are studied. As shown in the Table (Tab. 3.9), the maximum and minimum values of stance and swing are respectively selected. The figure (Fig. 3.13-Fig. 3.15) show the absolute peak values of each motion.

Tabelle 3.9: Knee Velocity vs Acceleration

Motions			Velocity[°/s]		Acceleration[°/s²]	
			Stance	Swing	Stance	Swing
1- Ascent	Min	Pos	135.26	148.38	694.3	2625
1- Ascent	Min	Neg	-171.63	-334.31	-1843	-1908
1- Ascent	Norm	Pos	143.69	139.12	693.73	2309.2
1- Ascent	Norm	Neg	-132.54	-348.74	-2004.6	-2271
1- Ascent	Max	Pos	158.23	127.36	763	2407
1- Ascent	Max	Neg	-87.1	-397.31	-1987	-2539
2-Descent	Min	Pos	17.32	308.96	1021	2879
2-Descent	Min	Neg	-227.47	-210.12	-934	-2425
2-Descent	Norm	Pos	7.7	323.32	1457	2846
2-Descent	Norm	Neg	-222.14	-185.72	-1051	-2503
2-Descent	Max	Pos	/	341.27	2188	2948
2-Descent	Max	Neg	-227.47	-131.99	-1064	-1938
2-Descent	Level walking	Pos	72.45	294.7	1423	3407
2-Descent	Level walking	Neg	-254.15	-256.4	-2134.7	-3742
3-Pick up loads	Squat 15Kg	Pos	102.97	/	304.98	/
3-Pick up loads	Squat 15Kg	Neg	-0.83		-204.3	
3-Pick up loads	Stoop 15Kg	Pos	2.91		50.84	
3-Pick up loads	Stoop 15Kg	Neg	-3.72		-49.67	
4-Walking	Walking	Pos	95.52	411.8	2706	4434.1
4-Walking	Walking	Neg	-362.07	-368.85	-2444	-6730
4-Walking	Jogging	Pos	207.35	605.65	6311	7239.7
4-Walking	Jogging	Neg	-372.33	-439.77	-6085	-9173.5
4-Walking	Running	Pos	230.23	693.37	7791.7	8614
4-Walking	Running	Neg	-397.29	-548.29	-7163.2	-11214

5-Climbing	Uphill 15%	**Pos**	94.71	254.94	1000	2855.3
		Neg	-243.1	-255.8	-1581	-1870
	Uphill 39%	**Pos**	159.62	144.99	1319.5	2431.5
		Neg	-218.77	-253.37	-1670.1	-1140.6
	0 Deg level	**Pos**	43.16	352.35	832.70	3621
		Neg	-231.74	-267.83	-1544	-2551
	Donwhill -15%	**Pos**	31.79	338.74	1226.6	3034.1
		Neg	-232.26	-222.49	-1503.6	-2661
	Donwhill -39%	**Pos**	/	360.63	1318	2550
		Neg	-183.61	-145.62	-962	-2664
6-STS	Sit to Stand	**Pos**	100.9	/	266.49	/
		Neg	-2.06		-316.43	
7-Jumping	Squat Jump(SJ)	**Pos**	573.77	28.82	4441.7	864
		Neg	-27.17	-57.24	-6399.2	-4800
8-Cycling		**Pos**	191.54	/	1189.9	/
		Neg	-196.44		-1980	
9-Recovery		**Pos**	/	599.09	/	14831
		Neg		-657.34		-11824

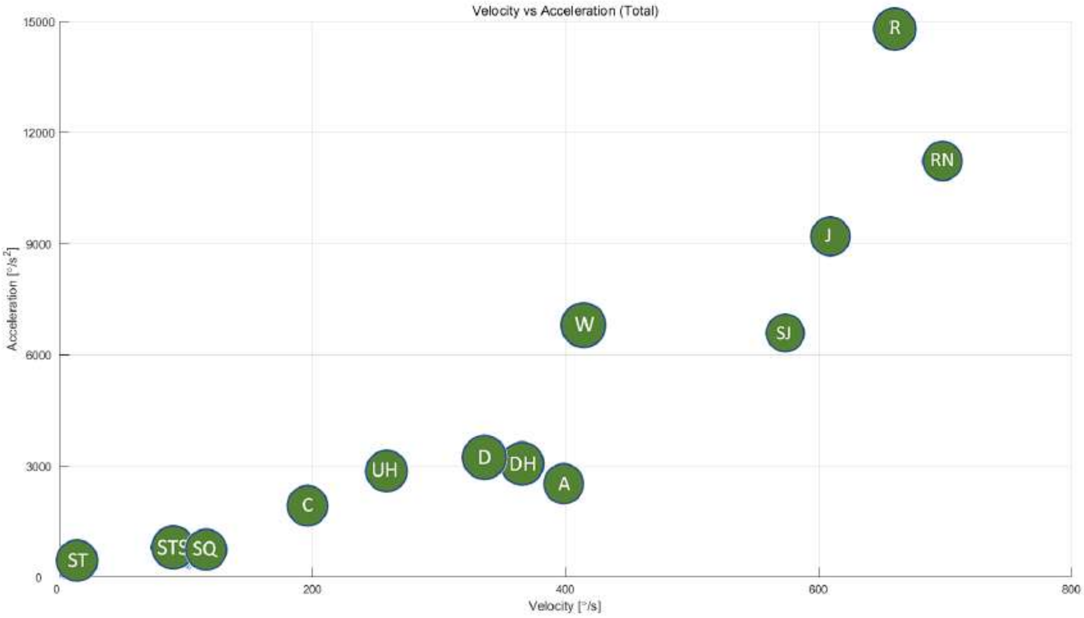

Abbildung 3.13: Knee Velocity vs Acceleration in Total phase

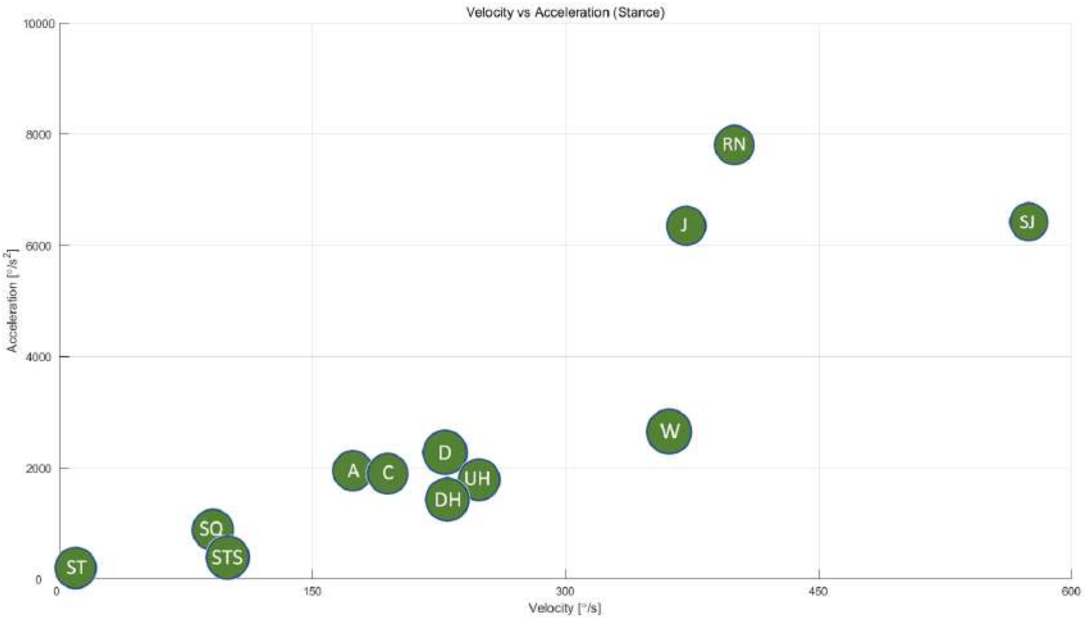

Abbildung 3.14: Knee Velocity vs Acceleration in Stance phase

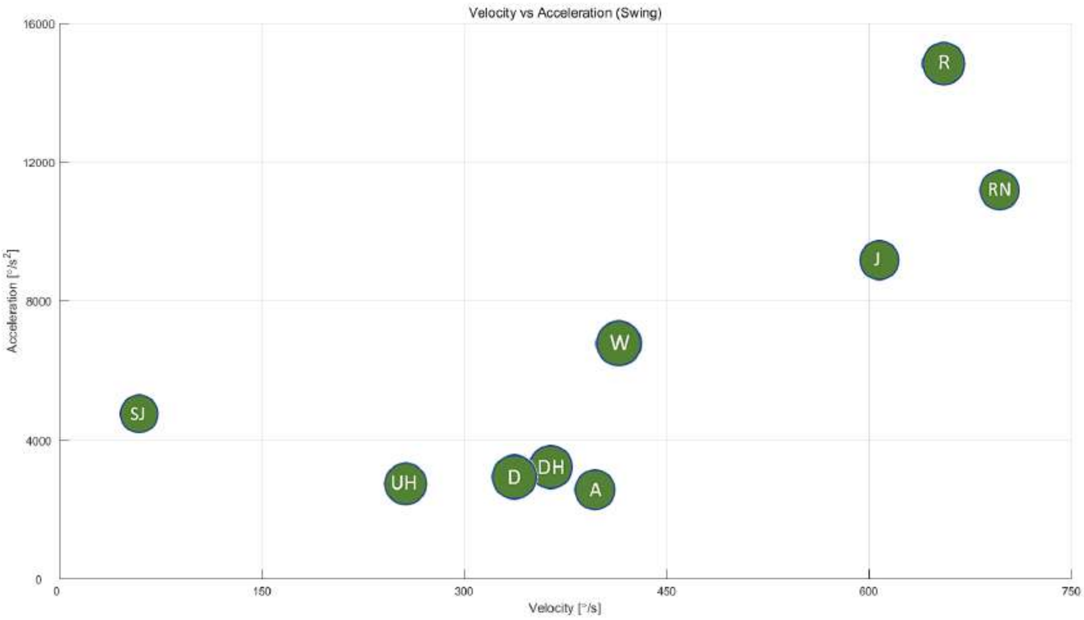

Abbildung 3.15: Knee Velocity vs Acceleration in Swing phase

The maximum angular velocity with 693 °/s and angular acceleration with 14831 $°/s^2$ respectively occurred in the late swing of RN-activity and R-activity. For most motions, the velocity and acceleration are larger in the swing phase than in the stance phase. However, the situation is opposite for SJ, which requires larger velocity and acceleration in stance (574 °/s and 6400 $°/s^2$). Because in SJ knee angles change quickly during entire stance (from 90° to 180° in 0.42s). In addition, although during SQ the ROM was maximum, the velocity and acceleration were small due to long gait cycle, only 103 °/s for speed and 305 $°/s^2$ for acceleration. The Following is kinetic analysis.

Tabelle 3.10: Knee Power vs Torque

Motions			Power [W/Kg] Stance	Power [W/Kg] Swing	Torque [Nm/Kg] Stance	Torque [Nm/Kg] Swing
1- Ascent	Min	Pos	2.19	0.6	0.91	0.03
		Neg	*-0.04*	-0.39	-0.17	-0.17
	Norm	Pos	2.69	0.65	1.08	0.03
		Neg	*-0.06*	-0.37	-0.22	-0.17
	Max	Pos	*2.87*	0.77	1.15	0.04
		Neg	*-0.02*	-0.3	-0.25	-0.2
2-Descent	Min	Pos	*0.27*	0.0012	1.23	0.35
		Neg	*-3.96*	-1.29	-0.04	-0.09
	Norm	Pos	*0.1*	0.0031	1.33	0.37
		Neg	*-4.37*	-1.22	-0.01	-0.09
	Max	Pos	/	/	1.46	0.21
		Neg	*-5.14*	-0.5	/	-0.08
	Level walking	Pos	*0.33*	0.01	0.47	0.21
		Neg	*-1.08*	-0.95	-0.29	-0.21
3-Pick up loads	Squat 15Kg	Pos	*0.23*	/	0.25	/
		Neg	*-0.86*		-0.4	
	Stoop 15Kg	Pos	/		/	
		Neg	*-0.38*		-1.49	
4-Walking	Walking	Pos	*1.55*	0.8	0.88	0.21
		Neg	*-1.71*	-1.5	-0.56	-0.44
	Jogging	Pos	*4.36*	0.76	2.51	0.12
		Neg	*-9.69*	-2.77	-0.27	-0.48
	Running	Pos	*4.64*	1.41	2.56	0.26
		Neg	*-9.91*	-5.15	-0.44	-0.73

5-Climbing	Uphill 15%	**Pos**	1.03	0.19	0.62	0.23
		Neg	-0.48	-1	*-0.68*	*-0.16*
	Uphill 39%	**Pos**	1.45	0.05	0.74	0.23
		Neg	-0.7	-1.01	-0.61	-0.16
	0 Deg level	**Pos**	0.56	0.28	0.39	0.21
		Neg	-0.35	*-0.9*	*-0.35*	-0.18
	Donwhill -15%	**Pos**	0.33	0.39	0.85	0.25
		Neg	-1.52	-0.94	*-0.23*	-0.16
	Donwhill -39%	**Pos**	0.35	0.34	1.22	0.33
		Neg	-2.46	-0.86	*-0.28*	-0.15
6-STS	Sit to Stand	**Pos**	*2.03*	/	2.37	/
		Neg	/		-0.06	
7-Jumping	Squat Jump(SJ)	**Pos**	*9.32*	0.04	1.43	0.06
		Neg	*-1.32*	-0.06	-0.16	-0.06
8-Cycling		**Pos**	1.49	/	*0.38*	/
		Neg	-0.05		*-0.14*	
9-Recovery		**Pos**	/	4.86	/	1.68
		Neg		-14.9		-1.37

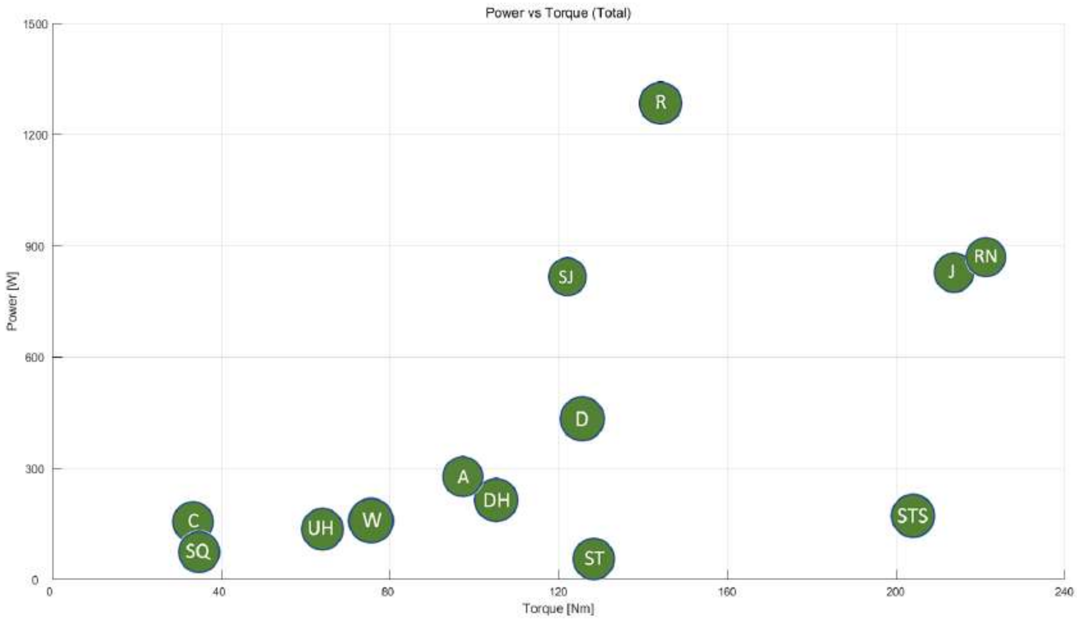

Abbildung 3.16: Knee Power vs Torque in Total phase

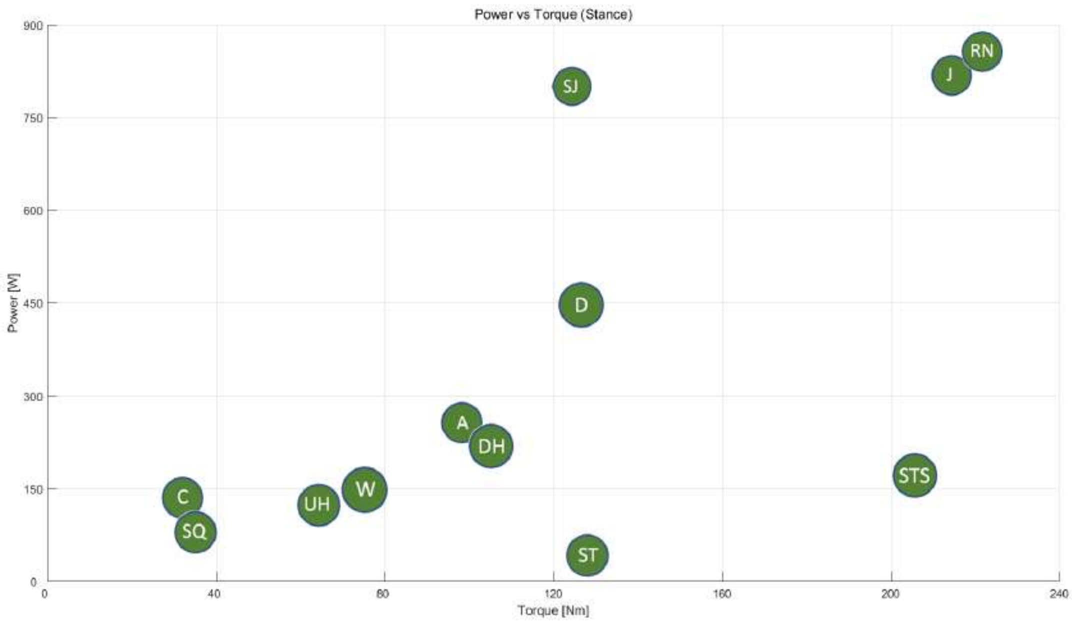

Abbildung 3.17: Knee Power vs Torque in Stance phase

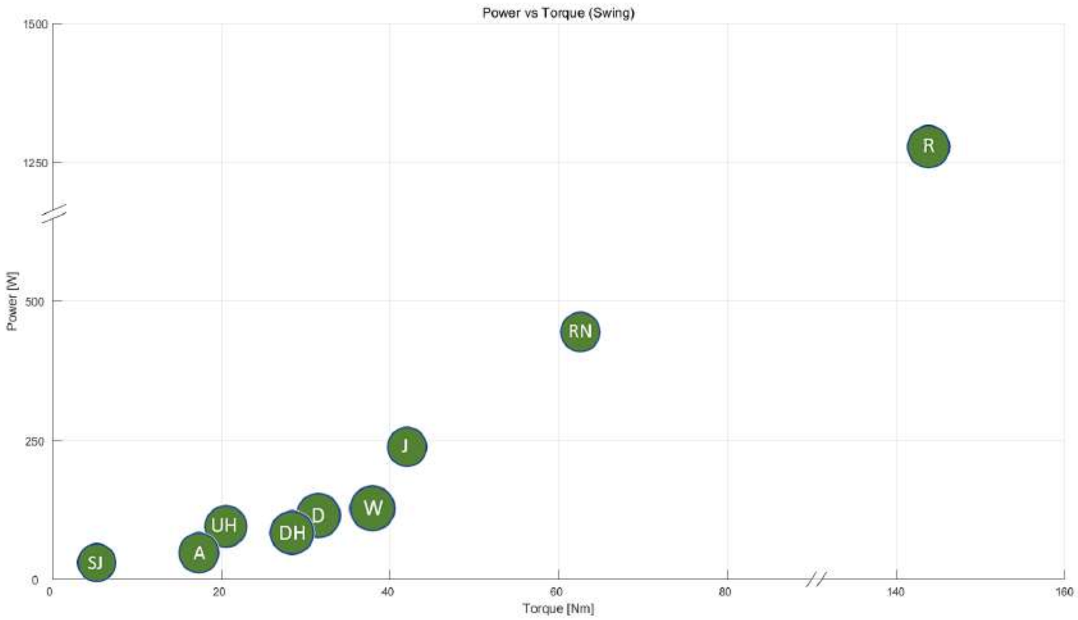

Abbildung 3.18: Knee Power vs Torque in Swing phase

Chart (Fig. 3.16) indicated that, the peak power with 1280 W was produced during R-activity, while the maximum torque with 220 Nm occurred during RN-activity. Furthermore, during STS-activity large torque (204 Nm) and small power (174 W) were produced. A similar relationship occurred in ST-activity with large torque (128 Nm) and very small power (33 W). Because the acceleration of stoop was fast zero. In addition, during SJ-activity the power was large with 800 W.

3.4.2 Discussion

Comparing the results with the hypotheses, it was found that the prediction of the peak power and peak velocity did not match the actual data. The maximum angular velocity occurred in the late swing of RN-activity, instead of R-activity. Because the angle range of running was larger than that of recovery. In RN-activity swing phase larger angles of knee are necessary in order to raise the limb and cover the distance as soon as possible. Therefore, the angular velocity during running was a little larger than that during R-activity. In addition, the peak power was produced during the swing of R-activity, instead of stance of SQ-activity. Muscle power is determined from the product of joint angular velocity and joint torque. In the late swing of the R-activity the large torque was quickly produced in order to decelerate knee extension in preparation for ground contact. Compared with SJ-activity, R-activity required more explosive power. The rest of the results were consistent with the predictions.

In addition to the peak values, there are also some results that are noticeable. For example, during C-activity the maximum extension angle with 130° was smaller than that of other motions. For C-activity the knee flexion angle highly depends on the saddle height. In this study the saddle height is approximately 109% of symphysis pubis height, a distance which has been found to require the least oxygen consumption [3]. Furthermore, during STS-activity large torque and small power were produced. Due to the vertical ascent of the body's center of gravity, STS transition requires high torque but low acceleration. So the power was small.

3.5 Ankle

In this section the Kinematics and Kinetics of each motion are going to be analyzed from the perspective of stance, swing and the whole motion itself. For the ankle all angles have been normalized in a sagittal plane to show 90 ° at standing position. That means that the negative kinematics is considered to be Dorsiflexion (DF), respectively for positive kinematics Plantar-Flexion (P-F).

3.5.1 Results

First and foremost, as shown in the figures below (Fig. 3.19) and (Fig. 3.20), the different forms of ankle have been plotted, which showing exactly the activities of the joint under different parameters for a complete gait cycle.

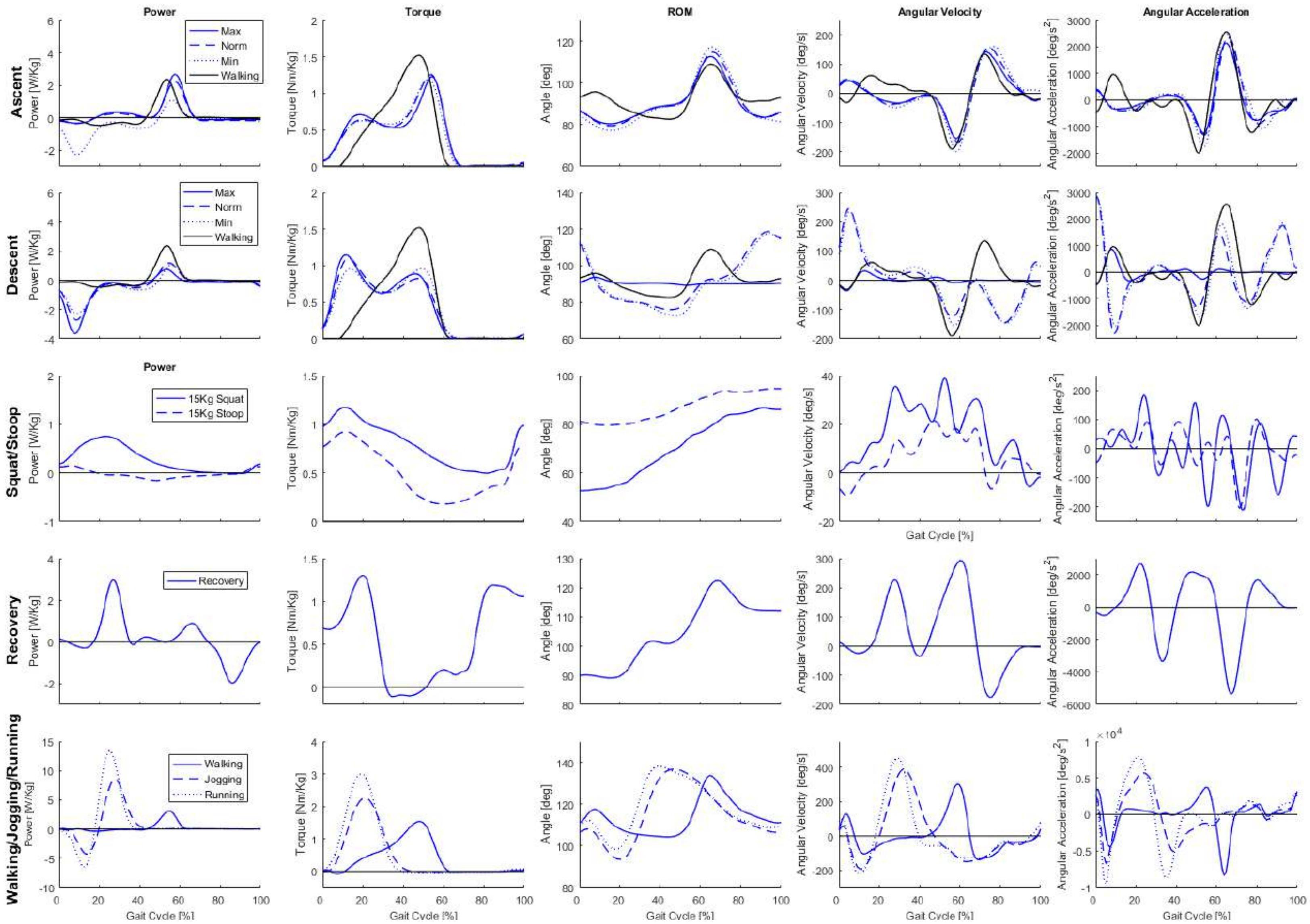

Abbildung 3.19: Ankle joint movement for Ascent, Descent, Pick up load, Recovery and Walking

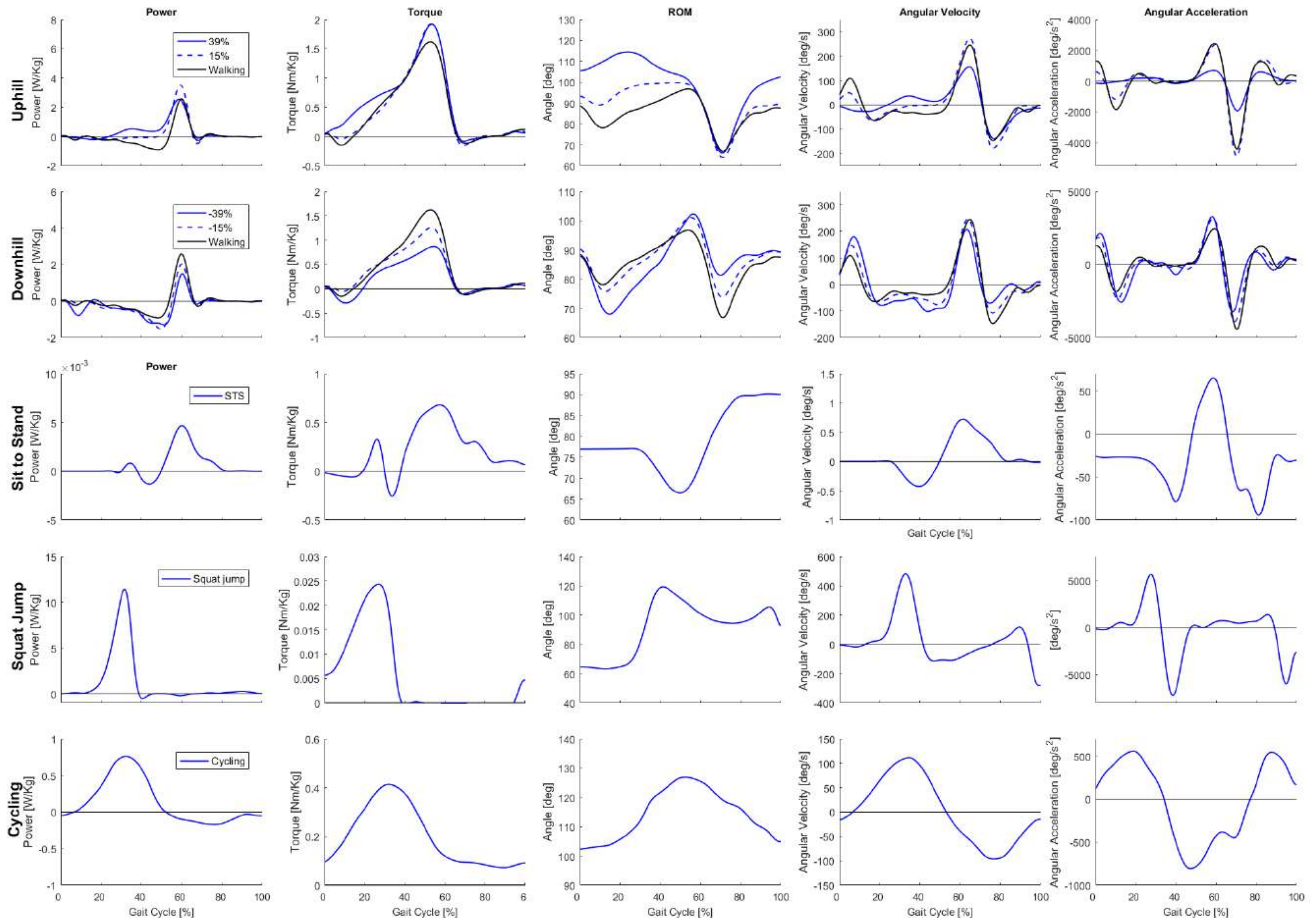

Abbildung 3.20: Ankle joint movement for Climbing, Sit to stand, Jump and Cycling

In (Table 2.11) the numerical values of the upper and lower ankle's ROM limit, for the analyzed activities, are shown. An overview of the intervals of each activity are provided in (Fig. 3.21).

Tabelle 3.11: Ankle ROM

Motions			ROM [°] Stance	ROM [°] Swing
1- Ascent	**Min**	**Max**	110.3	117.3
		Min	77.23	81.6
	Norm	**Max**	108	114.8
		Min	79.48	83.61
	Max	**Max**	106.1	112.6
		Min	80.42	83.5
2-Descent	**Min**	**Max**	11.4	117.8
		Min	72.6	88.63
	Norm	**Max**	108.7	118.8
		Min	76	90
	Max	**Max**	93.64	91.1
		Min	89.25	89.5
	Level walking	**Max**	104	109
		Min	82.6	91.07
3-Pick up loads	**Squat 15Kg**	**Max**	90	/
		Min	52.69	
	Stoop 15Kg	**Max**	90	
		Min	79.62	
4-Walking	**Walking**	**Max**	127.1	133.7
		Min	104.2	111
	Jogging	**Max**	130	136.7
		Min	93.48	106.4
	Running	**Max**	131.8	138.1
		Min	98.3	108.7

4-Walking	**Walking**	**Max**	127.1	133.7
		Min	104.2	111
	Jogging	**Max**	130	136.7
		Min	93.48	106.4
	Running	**Max**	131.8	138.1
		Min	98.3	108.7
5-Climbing	**Uphill 15%**	**Max**	100	89.64
		Min	89.05	64.03
	Uphill 39%	**Max**	114.4	102.5
		Min	88.06	66.08
	0 Deg level	**Max**	96.72	87.94
		Min	78.15	66.84
	Donwhill -15%	**Max**	101.1	90.78
		Min	75.79	73.9
	Donwhill -39%	**Max**	102.3	92.97
		Min	68.03	81.31
6-STS	**Sit to Stand**	**Max**	90	/
		Min	66	
7-Jumping	**Squat Jump(SJ)**	**Max**	119.4	119
		Min	63.32	92.69
8-Cycling		**Max**	126.9	/
		Min	102.4	
9-Recovery		**Max**	/	90
		Min		122.4

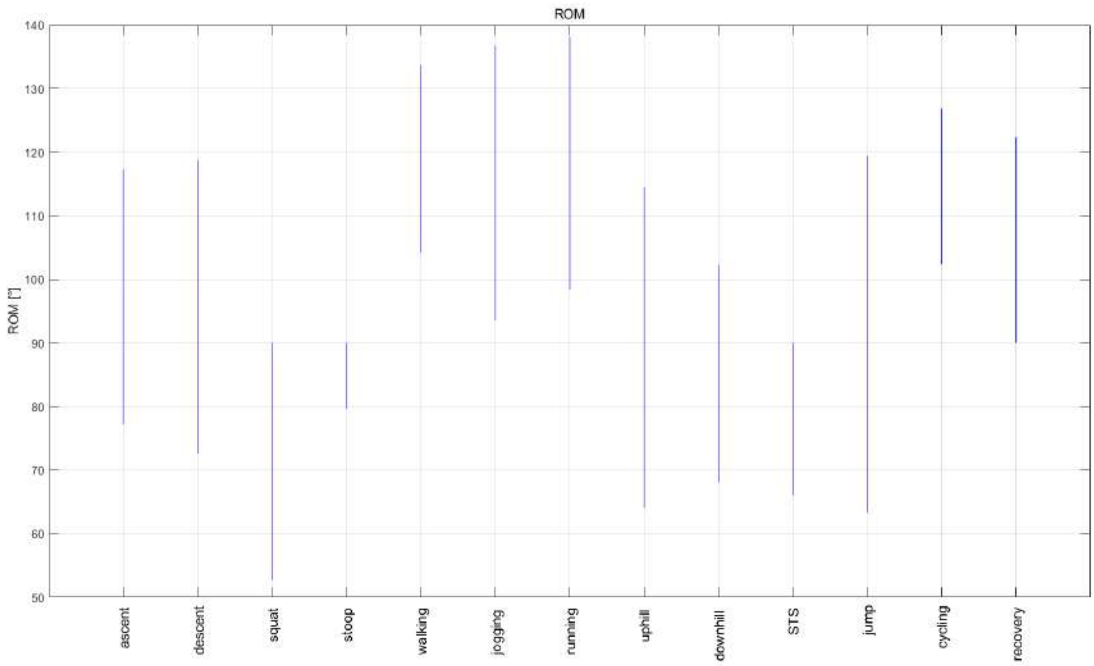

Abbildung 3.21: Ankle ROM

Firstly, starting with the SJ-activity has been shown [63.3 °-119.4 °], which is the biggest interval range of all activities, closely followed by UH-activity with [64 °-114.4 °] range. In addition to, the third biggest range was assigned to J-activity with range of [93.4 °-136.7 °]. Moreover, the ROM has shown and recorded the maximum DF for SQ-activity and the maximum P-E for RN-activity as well with 52.6 °, respectively 138.1 °.

Furthermore, the maximum results of the kinematics of the joint (red remarked) of all of the activities regards to the stance and swing phases, are shown in the table below (Table 2.12). Whilst, the maximum overall result of stance is all ready plotted as shown below (Fig. 3.23) as well as for Swing phase (Fig. 3.24). Where the total resultant for both phases is all ready plotted together as shown in the chart below (Fig. 3.22).

Tabelle 3.12: Ankle Velocity vs Acceleration

Motions			Velocity[°/s]		Acceleration[°/s²]	
			Stance	Swing	Stance	Swing
1- Ascent	Min	Pos	48.08	160.9	239	2542
		Neg	-199.6	-180	-1752	-1074
	Norm	Pos	49.4	157	242.5	2372
		Neg	-166.4	-25.5	-1312	-903.5
	Max	Pos	44.36	142.2	366.4	2140
		Neg	-154.3	-138.2	-1247	-764.3
2-Descent	Min	Pos	235.2	52.56	2766	1818
		Neg	-154.3	-145.9	-2016	-1351
	Norm	Pos	245.6	62.63	2879	1765
		Neg	-125	-145.2	-2302	-1149
	Max	Pos	32	0.55	867.7	115.7
		Neg	-35	-4.87	-322.5	-253.8
	Level walking	Pos	61.55	134.6	970	2571
		Neg	-190.1	-21.88	-1998	-1223
3-Pick up loads	Squat 15Kg	Pos	38.87	/	182.9	/
		Neg	-5.756		-210.6	
	Stoop 15Kg	Pos	21.44		101	
		Neg	-9.405		-204.2	
4-Walking	Walking	Pos	301.8	278.3	3712	3166
		Neg	-104.4	-138.3	-4461	-8335
	Jogging	Pos	387.4	243.5	5703	2598
		Neg	-192.3	-149.8	-6746	-5067
	Running	Pos	453.3	34.34	7964	2892
		Neg	-224.4	-131.7	-9515	-8747

5-Climbing	Uphill 15%	**Pos**	203.7	273.5	2360	2204
		Neg	-65.03	-178.5	-1172	-4884
	Uphill 39%	**Pos**	145.2	155.6	689.7	596.4
		Neg	-27.54	-139	-138	-1942
	0 Deg level	**Pos**	199.7	245	2447	1929
		Neg	-63.91	-146.7	-1861	-4439
	Donwhill -15%	**Pos**	234.3	246.5	3136	1229
		Neg	-75.86	-107.3	-2336	-3892
	Donwhill -39%	**Pos**	204.1	207.1	3276	857.9
		Neg	-101.5	-70.08	-2568	-3227
6-STS	Sit to Stand	**Pos**	0.86	/	65	/
		Neg	-0.92		-94.5	
7-Jumping	Squat Jump(SJ)	**Pos**	482.1	118.5	5599	223.8
		Neg	-27.28	-280.5	-7213	-5996
8-Cycling		**Pos**	111.2	/	558.3	/
		Neg	-96.33		-806.6	
9-Recovery		**Pos**	/	293.1	/	2669
		Neg		-175.1		-5347

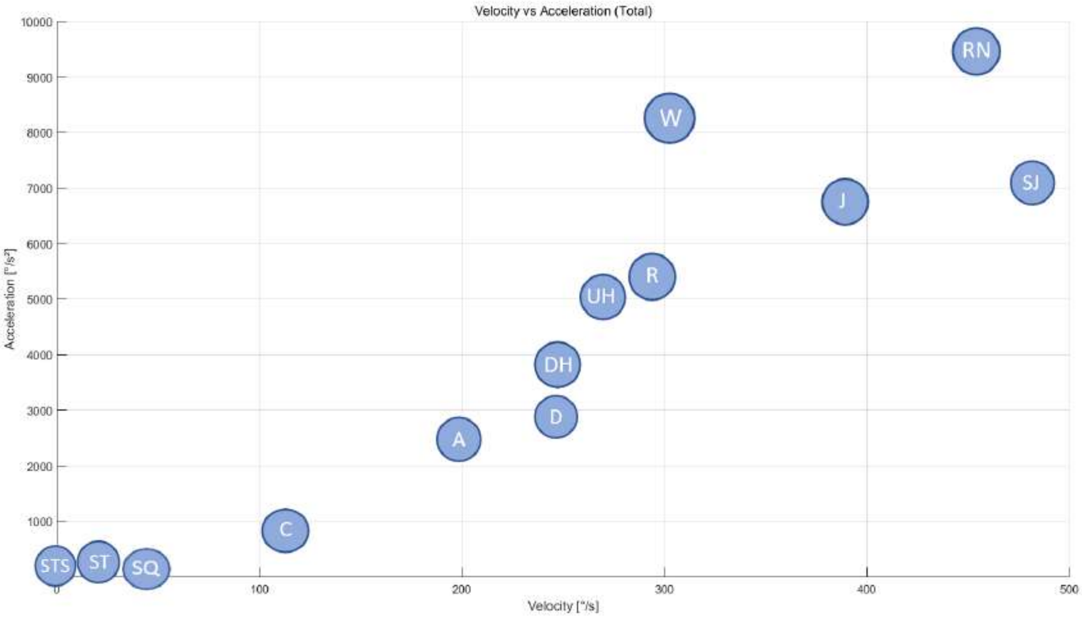

Abbildung 3.22: Ankle Velocity vs Acceleration in Total phase

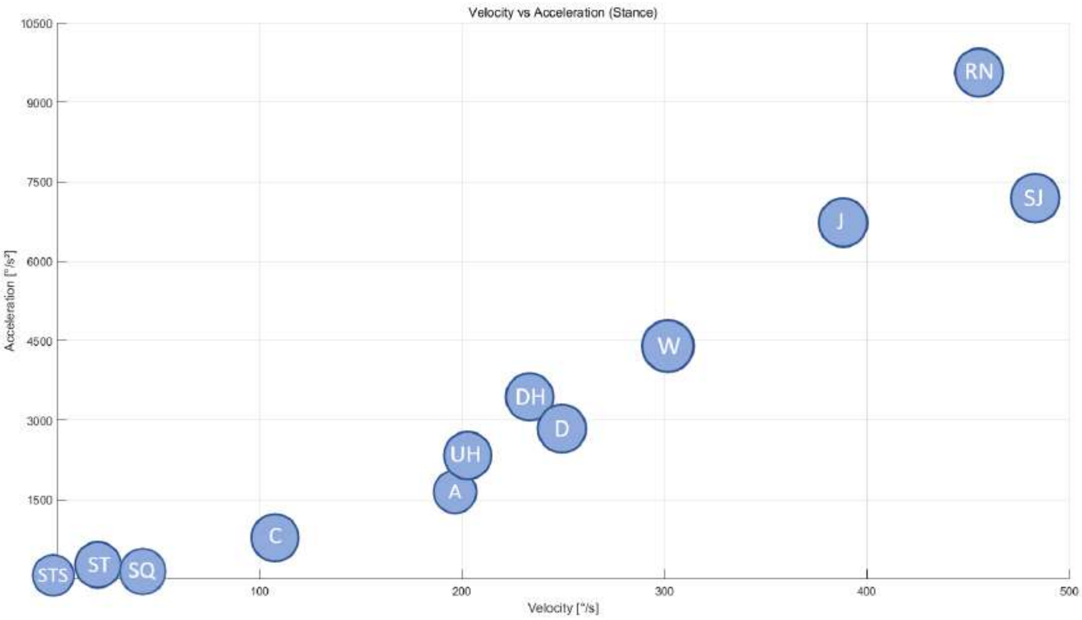

Abbildung 3.23: Ankle Velocity vs Acceleration in Stance phase

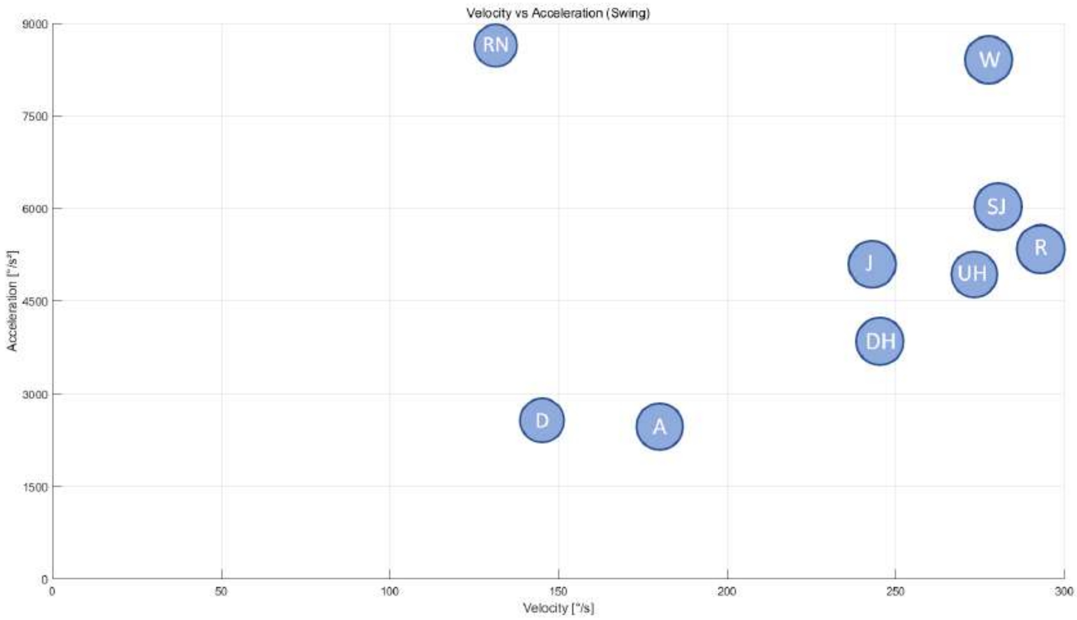

Abbildung 3.24: Ankle Velocity vs Acceleration in Swing phase

As shown in the resultant overall (Fig. 3.22), the maximum angular velocity has the recorded 482.1 °/s as the highest value for the SJ-activity, which occurred in the stance phase. In addition to, the RN-activity showed 453.3 °/s as the second highest value as all ready occurred in the stance phase. Lastly the J-activity recorded the third highest value at stance phase with 384.4 °/s.

On the other hand, regards to the angular acceleration, the maximum value recorded by the RN-activity with 9515 $°/s^2$ as occurred in the stance phase. Moreover, the W-activity showed the second highest activity the value of 8335 $°/s^2$, which occurred in the swing phase, followed by SJ-activity with a value of 7213 $°/s^2$ in stance phase.

Finally, regarding the kinetics of the ankle joint (red remarked) (Table 2.13) starting with the torque for the 50th percentile (Table 3.4), the value 257.7 Nm of RN-activity showed the highest value, which occurred in stance phase, followed by J-activity assigned 194.1 Nm in stance phase, which represents about 75.4 % of the maximum torque. Whilst, the UH-activity recorded the third highest value of 165.1 Nm, which assigned to the stance phase and represents about 64.1 %. On the other side, the maximum power value recorded in the stance phase of RN-activity with a value of 1153 W. Additionally, the SJ-activity assigned the second highest power value 982.6 W for the stance phase, which represents about 85.2 % of the maximum value. Lastly, the J-activity assigned the third highest power value with 728 W in the stance phase, which show about 63.1 % of the maximum value.

For the swing phase, as showed in the plot below (Fig. 3.27), the R-activity showed the maximum torque 111.9 Nm and the UH-activity showed the maximum power with 257.7 W.

Tabelle 3.13: Ankle Power vs Torque

Motions			Power [W/Kg]		Torque [Nm/Kg]	
			Stance	Swing	Stance	Swing
1- Ascent	Min	Pos	1.8	1.3	1.19	0.53
		Neg	*-0.33*	-1.3	/	-0.01
	Norm	Pos	2.22	1.86	1.25	0.64
		Neg	*-0.35*	-0.176	/	/
	Max	Pos	*2.67*	2.16	1.22	0.71
		Neg	*-0.33*	-0.122	/	/
2-Descent	Min	Pos	*1.07*	0.61	0.96	0.18
		Neg	*-2.22*	-0.266	/	/
	Norm	Pos	*1.18*	0.466	1.1	0.1713
		Neg	*-2.7*	-0.4	/	/
	Max	Pos	*0.75*	0.06	1.14	0.09
		Neg	*-3.64*	-0.38	/	-0.01
	Level walking	Pos	*2.37*	0.5	1.52	0.12
		Neg	*-0.46*	-0.08	-0.02	-0.02
3-Pick up loads	Squat 15Kg	Pos	*0.7531*	/	1.171	/
		Neg	*-0.1172*		/	
	Stoop 15Kg	Pos	*0.147*		0.9226	
		Neg	*-0.1567*		/	
4-Walking	Walking	Pos	*3.086*	*0.54*	1.533	0.104
		Neg	*-0.38*	/	-0.083	-0.027
	Jogging	Pos	*8.479*	0.927	2.26	0.164
		Neg	*-4.27*	/	/	-0.013
	Running	Pos	*13.43*	1.483	3	0.247
		Neg	*-6.504*	-0.025	/	-0.06

5-Climbing	Uphill 15%	Pos	3.527	3	*1.923*	*0.87*
		Neg	-0.187	-0.478	*-0.044*	*-0.157*
	Uphill 39%	Pos	2.547	1.49	*1.916*	0.6
		Neg	-0.2	-0.1174	/	-0.082
	0 Deg level	Pos	2.588	2.176	*1.618*	0.6167
		Neg	-0.916	-0.271	*-0.149*	-0.1171
	Donwhill -15%	Pos	2.043	1.424	*1.259*	0.356
		Neg	-1.533	-0.174	*-0.0528*	-0.094
	Donwhill -39%	Pos	1.5	0.931	*0.869*	0.259
		Neg	-1.292	-0.169	*-0.2859*	-0.107
6-STS	Sit to Stand	Pos	*0.26*	/	0.39	/
		Neg	*-0.06*		-0.14	
7-Jumping	Squat Jump(SJ)	Pos	*11.44*	0.019	0.0243	0.0044
		Neg	*-0.534*	-0.2	/	-0.000077
8-Cycling		Pos	0.76	/	*0.4134*	/
		Neg	-0.16		*0.072*	
9-Recovery		Pos	/	2.964	/	1.303
		Neg		-1.967		-0.107

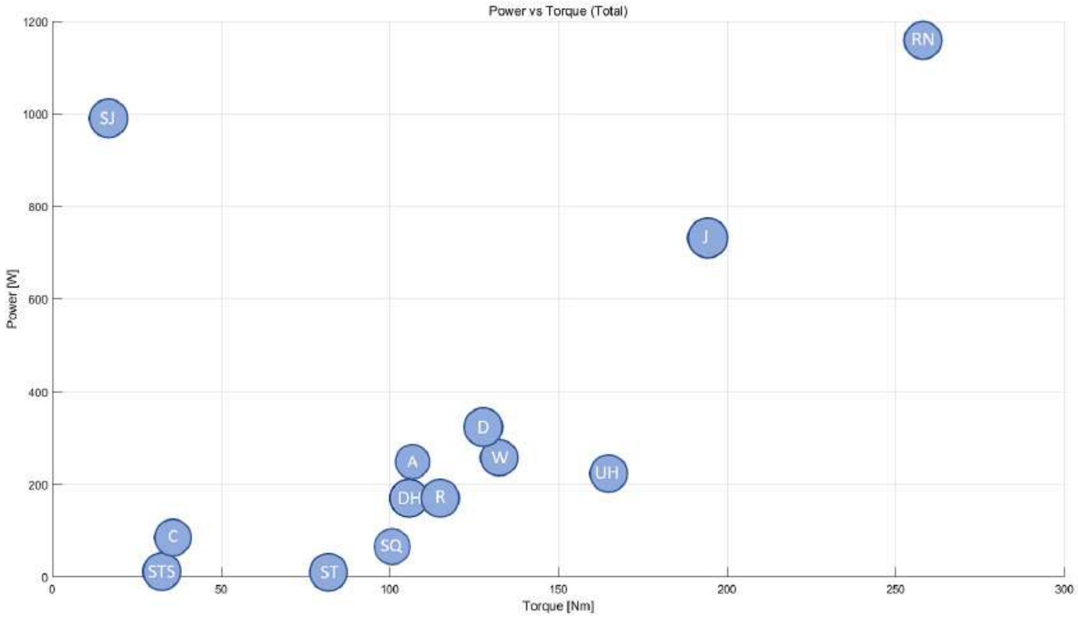

Abbildung 3.25: Ankle Power vs Torque in Total phase

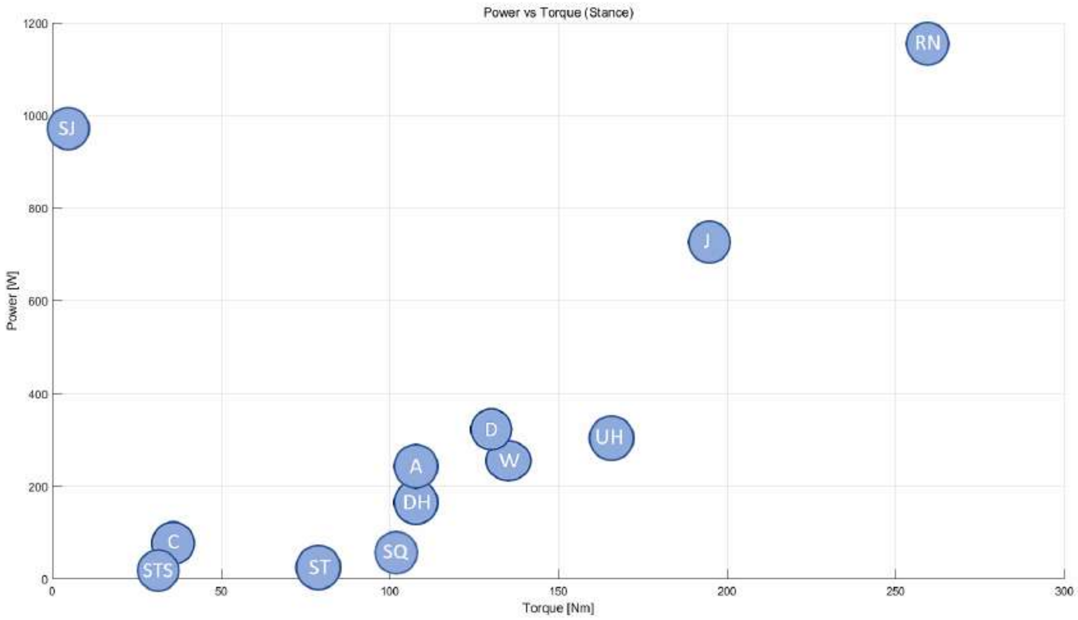

Abbildung 3.26: Ankle Power vs Torque in Stance phase

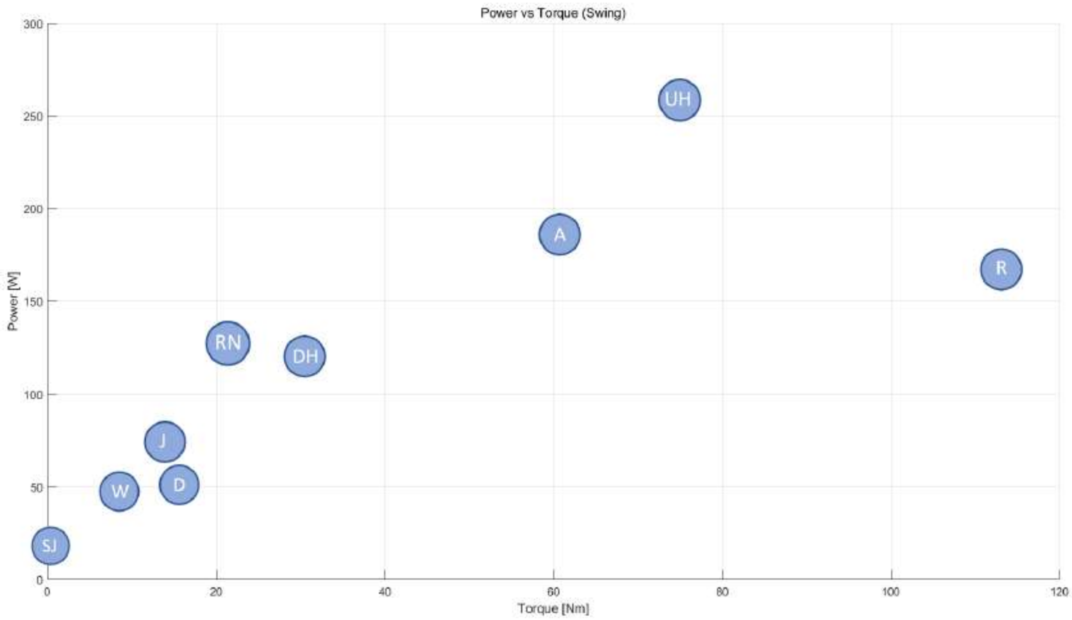

Abbildung 3.27: Ankle Power vs Torque in Swing phase

3.5.2 Discussion

Comparing the calculated result with the hypothesis, which all ready mentioned at the very beginning of the section (Sec. 3.10), showed a contradiction for the kinematics. Thus, the maximum angular velocity was occurred for SJ-activity at Stance phase, not for RN-activity at the swing phase. That's because of the body is trying to thrust itself quickly to produce the motion. On the other hand the results are showing also a contradiction with the hypothesis for the angular acceleration, So that the maximum angular acceleration was recorded for RN-activity at stance phase not at swing phase as predicted.

Finally, the maximum torque of the kinetics unexpectedly has been showed at the RN-activity at stance phase not at SQ-activity during the stance phase. The reason is that the ankle has developed large torque in order to push the body forward in the stance phase (Fig. 3.26). For the maximum power is confirmed with the hypothesis and recorded at RN-activity at the stance phase. And as well the reason of the RN-activity required not only high extending torque during the stance phase (Fig. 3.26), but also a high angular velocity which can be seen in the (Fig. 3.23).

3.6 Summary and Conclusion

The kinematic and kinetic parameter of hip, knee, ankle joint for 13 kinds of daily motion have been shown in this review paper. With the data of different requirements for 3 joints this paper can help the other researcher select suitable motors, springs and dampers in design of lower limbs prostheses.

Comparing the kinematic and kinetic parameters of hip, knee and ankle joint it is easy to find that knee joint requires the maximum power, which is 1279.91 W during R-activity in swing phase. Hip joint requires the maximum torque, which is 312.68 Nm during R-activity in swing phase. The maximum requirement of angular velocity for knee joint are also the maximum in 3 joints, which is 693.37 °/s during R-activity in swing phase. During R-activity in swing phase requires knee joint maximum angular acceleration, which is 14831 $°/s^2$.

In general the motor for knee needs to provide higher power, angular velocity and acceleration, motor for hip needs to provide higher torque but the requirement for power and angular velocity is not so high. In addition, the requirement of power and torque in stance phase is higher than in swing, but the situation for velocity and acceleration is related to joints. For hip higher velocity is required in swing phase than in stance but the situation of acceleration is opposite. For the knee joint higher velocity and acceleration are required in swing phase than in stance. For ankle joint higher velocity and acceleration are required in stance phase than in swing.

Further improvement in this paper can be: This paper only focus on the kinematic and kinetic parameters for lower limbs on sagittal plane. The muscles and ligaments create coronal plane moments to stabilize the body, so the research for parameters on coronal plane also plays a role for prostheses design[15]. On the other hand the data of 13 kinds of daily motions are acquired from different articles, so the data of participants are also different. For further research it can be useful to measure the kinematic and kinetic data for different daily motions with the same group of participants. It deserves to be mentioned that in this study we only focus on sit to stand but without stand to sit. The cycle of stand to sit is not simply the opposite of the cycle of sit to stand. For stand to sit knee joint needs lower torque than for sit to stand. Torque for stand to sit is required to maintain the sit-down speed, to let the body receive smaller impact.[18] Therefore, the kinematic and kinetic parameters should also be noticed in further research.

4 Reduce Power and Energy needs

This paper shows the needs in term of energy and peak power that a lower-limb joint requires for a daily activity. With the previous sections, a prosthetic legs' designer would figure out that those needs are high. Not only motors able to deliver such capacity are very expensive, but they also consume a lot of energy, thus requiring expensive and heavy high capacity batteries. Such problems can simply prevent designers from building affordable and comfortable prosthetic legs for people in need. However, mechanical principles exist and could be used to release the power consumption of the motor. The main two issues for a prosthetic leg design are:

- the maximum amount of instant power that the motor has to deliver (Peak Power)
- the energy that the motor will consume during the activity.

Throughout this section, existing principles which aim to decrease this two needs will be discussed. The general principles can be applied to the three joints. They are quite similar, and although ankle and knee are the most implanted (and so the most studied), the general principles shown here can be implemented for any leg-joint. The performances discussed here are generally taken from walking experiments (at desired speed) on people around 80 kg. Please take a look at the referenced original papers for more information on the experiments.

The question we try to answer through this section is:
What kind of mechanical principle can we apply to decrease power and energy needs to design a prosthetic leg?

Several principles are reviewed here, each contains its advantages and drawbacks, according to the activities and the joints a prosthetic designer is interested in, he can see what would be the minimal requirements he needs, and refer to this section to lower them if necessary. Of course, some of those principles could be useful even if a requirement can easily be fulfilled, as they embed other benefits (such as smoothing the movement).

4.1 Methods

To answer the question above, we investigate scientific papers and reviews, in order to find state-of-the-art manner of addressing these two issues. Only relevant work in term of feasibility and performance has been kept in order to summarize helpful systems. The papers are freely accessible, and have been found through Google Scholar, or were references of other papers dealing with the same subjects.

4.2 Gears and ball/lead screw

The first principle which needs to be implemented is the ability to transform the speed of the motor into torque. The use of such systems is mandatory to build a prosthetic leg, but the choice of a specific system already allow several motor/gearbox configurations for the joint. The motors produced by the industry have very large speed and a very low torque (a typical example, notably used in [7] is the Maxon motor RE-40 with a nominal speed of 6380 rpm and 94.9 mNm, link at [1]).

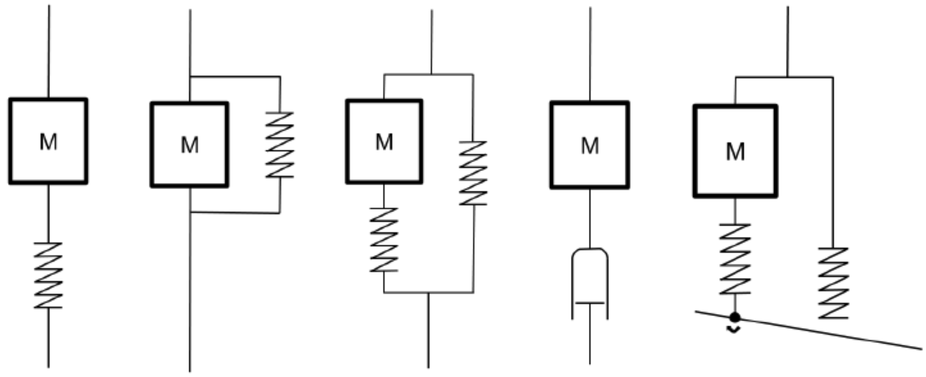

Abbildung 4.1: From right to left: spring in series, spring in parallel, series + parallel, damper, series + unilateral parallel spring, used in [2], agonist/antagonist separation, used in [14]

The most used devices for converting speed into torque in the industry are gears, that are combined inside gearboxes. Yet, the use of gears leads to two drawbacks:

- The maximum efficiency of a gearbox is around $\eta = 0\ 7$.
- The weight of those mechanisms is added to the total prosthetic weight.

Fortunately, prosthesis designers also have the possibility to use lead/ball screw devices, which can achieve higher efficiencies (as $\eta = 0\ 88$, with a specific design, described in [8]).
Ball screws have usually less friction and thus, heat less but are more noisy, bulky, and need a separated braking system. Lead screws on the other hand can self-lock and are cheaper.

4.3 Springs

Springs have been used a lot to reduce peak power and energy consumption. Their ability to store energy for later use is a great advantage for many daily movements, sit-to-stand for instance, but also in walking or running, where they accumulate energy during the first part of the stance phase (until the leg is perfectly aligned with the upper body) and release it during the second part. Very detailed properties about the use of different spring systems in prostheses are described in [6], where advantages and drawbacks of different architecture in use can be found.

4.3.1 Springs in series

The first natural attempt is to attach a spring and a motor in series. It was done in the paper [8], where the authors explain that with an adjusted stiffness, they were able to reduce energy consumption from 36 Joules to 21 and peak power from 250 to 77 W (per step), in a lightweight package (less than 1 kg). This is a very simple way of improving the performance, even if the use of a spring might act against the motor, and thus could also increase the motor power requirement.

4.3.2 Springs in parallel and S+P

Another approach is to use springs in parallel with the motor. However, parallel springs can even more act against the motor for certain tasks. For example, a spring used to help a compressing movement would act against the motor for the extension, requiring here much power and energy during this phase. This is why parallel springs are typically used with other mechanisms, as described hereafter. Yet, several designs show that in principle the peak power reduction is better with the parallel design than the series, whereas

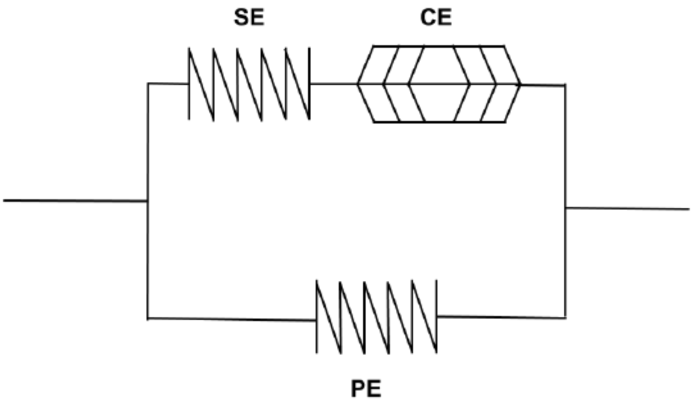

Abbildung 4.2: Hill Muscle Model (Series Element (SE), Contractile Element (CE) and Parallel Element (PE)

this last design is a better mechanical system for energy saving.
Combining two springs in parallel and series takes advantages of the two models. We can notice that such a design (S+P) is also closer to the Hill Muscle Model (cf Fig. 4.2), composed of a series and parallel spring (combined to a Contractile Element). Another advantage of structures combining several springs is the possibility to adjust several stiffnesses.

However, as quoted before, the use of a parallel spring might act against the motor, reducing its potential efficiency, particularly in terms of energy. Such a design is implemented and described by MIT researchers in [2], where the authors also use another principle to counter the drawback of parallelism: unidirectional parallel spring, described in the next section.

4.3.3 Unidirectional Springs

As pointed out, the main problem of springs is that they act against the actuator for the movement they are not meant to help. To counter this drawback, several techniques have been developed. One idea is to have the spring detached for the part of the movement when it could act against the motor, and connect it once it optimally helps. This kind of advantaged is reached in [14], where the authors combined unidirectional springs with another consequent design improvement (c.f. Section 4.6), but also in [2]. In this last paper, this principle is used by the researchers, through a unidirectional spring. It also helps to avoid hindering the foot motion during the swing phase, as it acts only when the angle of the ankle is greater than zero (as showed by the last image of figure Fig. 4.1). The use of this system is said to improve the energy efficiency from 7 % to 20 %, compared to a passive-elastic prostheses, even if the motorized device is twice as heavy, for a gait activity at self-desired speed.

4.4 Clutches

Another way to deal with the problem of springs acting against the system is to use clutches. Clutches are not used to store energy or reduce peak power per se, but are combined with other mechanisms to get the best out of those. As for unidirectional springs, clutches are also often used to engage and disengage the parallel elasticity between stance and swing phase (for which there is a need between the need of a movement and its opposite). They are usually used in the drive train, but in [7], the authors use a clutched parallel elastic actuator (CPEA), to disengage the spring in case of energy releasing needs. This solution seems more interesting as it is cheaper and compact. The design is said to help reduce the energy consumption of the actuator of 80 % and the Peak Torque requirement by 66 % for a human rebounding task, with the simple trigger-based control, and decrease the weight of the mechanism of 20 %.

4.5 Dampers

Dampers are a lot used in mechanical industries to absorb chocs, as they reduce the motion by using viscous friction. This mechanical principle is mostly used in semi-active prosthetic legs to help reduce the movement (producing negative work). Most of the time, linear dampers are embedded in the prosthetic device. They are used in order to mimic the natural flexible joints, that absorb chocs. They are mainly implemented for the knee prostheses, whose action in walking or running is mainly to resist the movement. Dampers soften the contact with the ground, notably for comfortable slope and stairs descent.
The drawback of dampers is that they are made to dissipate the energy. Thus, adding a damper usually conduct to rise the energy consumption of a device. However, in [6], authors reveal the possibility of using dampers to produce an electrical energy of 2.4 W while braking at the end of the swing phase. This recovered energy might also be directly used for another joint (ankle, hip), or to reload batteries. We can think about extending this principle to use it during other activities, which require greater braking action (as stairs decent, sitting... etc). Another advantage is that dampers can include a control of the damping ratio, useful to adapt different usage, or gait speeds.

4.6 Agonist-antagonist separation

The use of unidirectional springs is also done in [14], where the authors have decided to separate the actuator responsible for the agonist movement from the antagonist one (cf Fig. 4.1). They have incorporated in their design several previously mentioned principles to build a prosthetic knee (variable dampers, series unidirectional springs, series elastic clutches). Here the prosthesis is behaving as agonist-antagonist series-elastic clutch elements during the stance phase and as a variable-damper during the swing phase. The control process to achieve such a mechanical behavior is clearly described in their paper, as long as the mechanical design.
The authors have thus designed a new way to solve the problem of springs acting against the system with this prosthesis, which requires an energy consumption of 8 W (whereas direct drive systems require more than 25 W), leading to a 130 g battery need. Finally, as the knee joint is here fully motorized and contains a series-spring, it allows more energetically expensive tasks, such as stair/slope climbing, or sit-to-stand. The drawback of such a system is that it needs a lot of optimization research to adjust all the small parameters (optimal spring rates for instance).

4.7 Variable stiffness actuators

An unseen, and yet, very important problem so far for prosthetic designers is that the amount of saved energy or peak power decrease depends on hyperparameters that designers have to tune. The perfect stiffness of a spring to minimize peak power or energy waste depends on a lot of parameters. Some of those parameters depend on the person who use the prosthetic leg, but others are gait speed or slope for example. Thus, another feature allowing peak power reduction and energy save across different daily activities would be to change the stiffness of the embedded springs, which is done notably by using Variable Stiffness Actuators (VSA). Such systems require a specific motor to change the stiffness.
In [4], authors have been able to decrease the peak power by a factor 17, nearly corresponding to the minimum theoretical value, i.e. the mean power produced by the joint during a walking cycle. To achieve such a result, they modify the variable system, and thus the resonance, within the gait cycle. They show

here that VSA can be used to adapt different situations with different parameters (walking, running, climbing stairs...), but also during an activity.

4.8 Systems Already in use

We have seen several mechanical system to answer our question in this section. We summarize the different principles studied in this paper in the table page 55, with reference to papers where they are used and further described. Some are used in every design, and thus papers, but not described through all of them (like gears/ball screw). Information is here compressed, if you are interested in the principle and want to investigate further, please refer to the corresponding section or the original paper.

4.9 Conclusion

We have described among this section several mechanical principles, aiming at reducing the power and energy need of motors in active prosthetic legs. Some of those principles also embed other advantages, as dampers which can smooth the movement. The last described principle are much more complicated than the first, as they are extensions which try to modify those to tackle their drawbacks.

We haven't spoken about controller, which are a very important part of this kind of prostheses. Still, we would like to underline the need of an accurate controller to manage the actuators of those limbs, such that they can fully adapt the body of the owner.

Mechanical principle		Joint	Activity	Advantage	Drawback	Paper
speed/torque converter	Gears	ankle	gait	small if combined in gearboxes	lower efficiency than lead screws	[8] [7]
	ball/lead screws	ankle	Gait	Higher efficiency	more expensive	[8] [6]
springs	series	ankle/knee	gait	Reduce energy consumption	optimal stiffness search	[8] [6]
	parallel	ankle/knee	gait	reduce peak power	optimal stiffness search More likely to act against the motor	[6]
	S + P	ankle	gait	reduce peak power and energy consumption	optimal stiffness search Parallel can act against the motor	[6] [2]
	unidirectional	ankle	gait	can prevent action against the motor	Optimal & fixed engagement angle	[2]
clutches		knee	gait rebound	allow spring engagement and disengagement	accurate control need	[7]
dampers		knee	gait run	Smooth movement can retrieve energy adapting damping ratio	inevitable loss of energy	[6]
agonist/antagonist separation		knee	gait	consequent energy save several stiffnesses unidirectional motor	two motors need can retrieve energy stiffnesses adjustment	[14]
variable stiffness actuators		ankle	gait	consequent energy and peak power reduction (when optimized)	two motors need real-time stiffness adjustment	[4]

Tabelle 4.1: Summary of mechanical principles

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