SUMMARY
The purpose of this study was to quantify different strategies in neuromuscular activation patterns between and within muscle groups while walking. Electromyograms recorded from the thigh muscles were submitted to a time/frequency analysis using wavelets. The results showed that the obtained power for the different time points reflects muscle-specific inter-muscular activation patterns. A muscle-specific shape and a precise peak intensity occurrence were obtained within Mm. quadriceps femoris.

INTRODUCTION
The knee is, due to its anatomical position, muscles and structures around the joint, a complex structure which is prone to injury. The dynamic interplay between these muscles is an important consideration when attempting to understand normal gait. Human gait is a constant and repetitive movement involving the activation of multiple muscles in a specific sequence of events occurring at a precise time point [1]. The understanding of the timing aspect as well as of the interplay between synergistic, agonistic and antagonistic muscles that surround the knee joint is crucial for the knowledge about how muscles work together in healthy females. The aim of this study was to describe and quantify how individual thigh muscles control the knee joint at heel strike during normal gait. The focus was on the neuromuscular “fine-timing”.

METHODS
The muscle activity was monitored by surface electromyography (EMG) (2500 Hz, Biovision, Wehrheim, D) of Mm. rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), semitendinosus (ST) and biceps femoris (BF) in 10 healthy females while walking. The placement of the bipolar surface electrodes was done according to the SENIAM recommendations. Waveforms indicating the power of the EMG over time (500 time points centered at heel strike) were extracted by a wavelet method [2] across the centre frequencies of 92, 128, 170, 218, 272, 331, and 395 Hz and were normalized to power 1. The individual waveforms of each subject were obtained by averaging the waveforms of all steps (between 18 and 24 steps). The group average was computed from the subjects' individual waveforms and was sent to a peak detection to identify the locations of all peaks with a higher intensity level than 1% of the maximum peak value [3]. A raster plot was generated for showing the location of the peak intensities with a time resolution of 6 ms and the peak distribution across the different muscles (y-axis).

RESULTS AND DISCUSSION
The group average waveforms representing the power of the EMG signals of the quadriceps (QF: RF, VM, VL) and hamstring (HAM: ST, BF) muscle groups are shown in Figure 1. These power waveforms show the basic muscle activation strategies whereas the subject’s individual average waveforms indicate the ‘fine-timing’ around heel strike (not shown in the results). QF, ST and BF are mainly active in the early post, pre heel strike period and between -200 and +50 ms, respectively.

The raster plot (Figure 2) illustrates the interplay between agonistic and antagonistic muscles, but also the synergistic effects within QF and HAM. The vertical alignment of the dots at around +35 ms for RF, VM and VL illustrate a precise inter-muscular with a muscle group-specific timing of the intensity peaks (synergistic effect) (Figure 2, three top rows). As there were an averaging process the waveforms of QF are congruent waveforms and have a precise timing (Figure 1 & Figure 2, top three rows). This result indicated that contraction of RF, in spite of a biarticular muscle, resulted mainly in knee extension. Such a synergistic interplay in QF could be the product of a programmed function controlled by the CNS. Additionally, the high level of
inter-muscular coordination of VM and VL may be valuable synergists to stabilize the patella and this synergistic activation may be used for the transverse knee joint stability. It is known that an unbalanced activation of VM and VL leads to a patellar maltracking shown in patellofemoral pain patients [4].

![Raster plot with the timing of the intensity peaks (x-axis) detected in the power waveforms are illustrated across RF, VM, VL, ST, and BF (y-axis). Time 0 indicates heel strike (vertical line).](image)

**Figure 2**: Raster plot with the timing of the intensity peaks (x-axis) detected in the power waveforms are illustrated across RF, VM, VL, ST, and BF (y-axis). Time 0 indicates heel strike (vertical line).

In contrast to QF, the waveforms of HAM had a high inter-muscular variation in shape and a low inter-muscular timing/coordination of its intensity peaks (Fig. 2, two bottom rows). ST and BF demonstrated a differently strategy of their peak intensities while walking which could have originated from morphological, anatomical and/or functional variations. Especially, the timing aspect of BF and ST revealed conspicuous inter-muscular variations with asymmetry in HAM co-activation.

Interestingly, a co-contraction of QF and ST (agonist-antagonist activation) with a time shift of the intensity peaks was found in the post heel strike period, whereas ST had its intensity peaks 20 ms earlier than QF (Figure 2). Shifts in timing in the post heel strike period may indicate different effects of muscle activity on the knee joint and in the case of ST on the hip joint. At heel strike, ST acts more as a hip extensor than a knee flexor as shown in a dynamic model [5]. In the intact knee joint, activation of the agonist QF generates a forward shear force on the tibia with respect to the femur and HAM has the potential to counteract this forward force by co-activation during knee extension. Moreover, HAM has the potential to reduce the rotation of the tibia produced by contraction of QF. These results reflect the specific roles of the major muscles during walking.

Especially around heel strike where the body is exposed to impact forces, a high degree of simultaneous muscle activity achieves preparatory knee positioning and regulates the stiffness of the muscular system to tolerate and absorb high impacts in order to stabilize the knee joint. Such a recruitment pattern produces a dynamic knee joint stability [6].

**CONCLUSIONS**

The present study shows that the level of inter-muscular coordination is muscle-specific and that the muscular activation patterns in QF are highly precise in shape and timing. The synergistic effect between muscles and the agonist-antagonist interplay of muscles around the knee joint is important for understanding the mechanics of the knee joint and how the impact will be controlled by the neuromuscular system.

**ACKNOWLEDGEMENTS**

This study was supported by: Emilia Guggenheim-Schnurr foundation, ProMotio foundation and the donation of H.J. Wyss to the University of Basel.

**REFERENCES**