Animal tissue cells (as fibroblasts and keratinocytes) are utilising a unique principle of locomotion: the adhesive cell migration for crawling on a fixed substratum. It is a highly complex process involving the cytoskeleton and multiple regulation mechanisms ([1] and [2]). The moving cell is polarised as a result of asymmetric cytoskeleton modifications by assembling and disassembling microfilaments ([3] and [4]). Single G-Actin molecules are polymerised to bundled and branched F-Actin filaments at the cell’s frontal leading edge, resulting in an inner pressure on the frontal plasma membrane ([5] and [6]). Transmembrane glycoproteins such as integrins are surface receptors ([7]), they adhere to the substratum and cluster to a focal complex ([8]). Inside the cell these receptors are dynamically bound to actin filaments which are cross-linked to myosin dimers ([9]). By exertion of contractile stress this actomyosin complex is able to transfer a traction force onto the substratum, enhancing cell polarisation: at the front, ‘soft’ centripetal forces pull the cell body forwards, whereas in the rear, ‘stiff’ centripetal forces mechanically disrupts the cell from the substratum ([10]).

This project is using the basic physical principles causing the propulsion during cell migration as a bio-inspired approach for designing a new form of crawling robot locomotion. The aim is not to copy the cell migration mechanism itself but rather its basic physical principle. This principle consists of an autonomously induced gradient of stiffness of the adhering cell cortex, increasing from front to rear, persisting during migration due to the successive assembly and strengthening of microfilaments at the adhesion sites. These physical properties are implemented into a computational model with corresponding simulations of an autonomous self-crawling and self-deforming robot.

The computer based simulations are used with the intention that the model is simple.
enough for construction in reality. This leads to possibly new forms of crawling locomotion in robotics, advantageous in situations, where legged and wheeled propulsion is not usable or working.

The technical approach of the two-dimensional computational robot model consists of an inner and an outer chain with elastic segments in an over-damped system. The nodes of the two chains are linked by additional elastic radial segments. The segments of the inner chain are relatively stiff in their elastic properties (representing the tangential actin fibres) compared to the segments of the outer chain, which are much softer (representing the plasma membrane tension). Additionally, the inner segments tend to straighten, causing torsion forces on each segment. The outer nodes adhere to a ground surface when they touch this surface. During adhesion the linking radial segments (corresponding to the outer adherent nodes) adapt and change their mechanic properties and dynamic behaviour: their base lengths decrease during adhesion (becoming more 'stiff'), thereby building up a gradient of stiffness over time. After disruption the base length again increases. Disruption is caused by exceeding a certain vertical force limit at this node. This adaptation in adhesion of the outer chain nodes represents the motor of the model, because the radial segments need energy by either becoming stiff or by becoming softer again after disruption, with the preference to actively adapt to adhesion and passively revert to non-adhesion state. Additionally to the elastic and torsion forces, pressure equilibration forces, friction and gravity contribute to the node’s force equilibrium, therefore each node has a velocity and a resulting dynamic displacement.

The number of nodes and segments of the model’s chains is limited by a compromise between less complexity and better moving characteristics. In this case each chain consists of 16 nodes and segments, which does not add too much complexity but enhances the 'rolling' characteristics of the chains during movement.

Repeated simulation runs show that the described computational model is able to move on a ground surface, and that the whole movement of the model is stable. Further simulation experiments with changed parameters also reveal that it is capable to move upwards a surface with high inclination or walls without losing stability. The periodicity is similar to the one in simulations without inclination.

The main insight of these simulations indicates that this bio-inspired mechanical crawling robot model is capable of self-deforming and moving autonomously, heterogeneously and directionally (with harmonised and optimised model parameters). No additional outside forces (to pull or to push the model) are required for movement. The major contribution of its motility is caused by the forces of the adherent nodes, causing a traction force on the surface (much like a living migrating cell). Once the robot model has started to move, it does not stop (as long as a sufficient supply of energy is provided for the stiffness adaptation).

The capability to move upwards an inclined surface is a very promising feature of this model, because it is equivalent to pulling or transporting an additional load on a surface without inclination. Furthermore, this kind of locomotion is adhesion-based, so that it is
usable in scenarios, for instance inside of pipelines, where no other common mechanical propulsion types are usable.

References


